Planning and Designing Research Animal Facilities

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Planning and Designing Research Animal Facilities

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PLANNING AND DESIGNING RESEARCH ANIMAL FACILITIES

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Food for Thought

In the first, and until this book, only comprehensive book on the subject of planning laboratory animal facilities edited by Theodorus Ruys and published by Van Nostrand Reinhold in 1991, Ted included the following quotation that the editors of this book consider worth repeating:

> It's unwise to pay too much … but it's worse to pay too little. When you pay too much, you lose a little money … that is all. When you pay too little, you sometimes lose everything, because the thing you bought was incapable of doing the thing it was bought to do. The common law of business balance prohibits paying a little and getting a lot … it can't be done. If you deal with the lowest bidder it is well to add something for the risk you run. And if you do that, you will have enough to pay for something better.
>
> *John Ruskin*

The following echoes Ruskin's sentiment:

> Cheap is not necessarily inexpensive and all too frequently it is not.

Also relevant to planning and designing research animal facilities is the following sentiment:

> If a poor design makes a routine task difficult to do, it will not be done routinely and certainly will not be done efficiently.
>
> *Jack R. Hessler*
> *Noel D. M. Lehner*

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Preface

The American College of Laboratory Medicine, from its beginning, has had goals to advance knowledge and education in laboratory animal science and medicine. The College continues this mission with the publication of this book, *Planning and Designing Research Animal Facilities*.

This is a timely subject, as we are in the midst of a biological revolution. Research institutions have built, expanded and renovated animal research facilities, or are planning to do so, to keep up with the demands of biomedical research caused in part by growth in the use of genetically altered rodents and the upsurge of research in infectious diseases.

Planning and designing any facility is a creative process, and animal research facilities are certainly no exception. There are multiple solutions to address the myriad of factors that influence the design and construction of research animal facilities. There is no "best" design applicable for all facilities, and arguably not even a single "best" design for a given facility. For this reason, this is not intended to be a "how-to" book. The goal is to cover the basic programmatic requirements of animal research facilities, providing ideas for meeting those requirements while, hopefully, stimulating the creative process in which designers in consultation with those who work in research animal facilities generate even better ideas. That is how progress has been made and will continue to be so.

This requires in-depth knowledge and understanding of all aspects of animal research facilities, architectural, engineering, construction and programmatic requirements. Such a broad range of knowledge and experience requires a team of individuals. Information in this book is intended to facilitate communication between the various disciplines, provide contemporary information, and stimulate creativity that will help lead to wise decisions and advance the knowledge base for planning, design and constructing research animal facilities.

We are indebted to the authors who contributed their knowledge and experience that has made this book possible. We also wish to thank the many reviewers whose efforts have made the book a better one.

Jack R. Hessler
Noel D. M. Lehner

Introduction

Jack R. Hessler and Noel D.M. Lehner

The primary focus of all animal research facility planning and design must be on controlling variables in the research animal's environment. Environmental factors may affect biological responses to experimental variables, potentially confounding experimental data and results (Faith and Hessler, 2006; see also Chapter 7 in this book). There are many factors that must be considered, including genetic, microbial, chemical and physical factors. Control of genetic variables is primarily a matter of biology, but control of other variables is dependent to a significant degree on the design and management of the research animal facility. Properly designed facilities greatly facilitate the effective management and high quality day-to-day animal care that is required to optimally support animal research and testing. Precisely what controlling the research animal's environment means has been, and will continue to be, an evolving process driven primarily by increasing levels of scientific knowledge and sophistication. Improvement in the quality of the animal environment must go well beyond that required to assure the animal's well-being to keep pace with the advances of science.

There are three basic categories of animal research facilities, based on the primary activity they support: (1) commercial animal production of research animals, (2) safety and toxicity testing, and (3) biomedical research and development. Each has unique programmatic requirements, but all have many common requirements. Much of the information provided in this book is applicable to all three, but focuses primarily on biomedical research and development facilities.

Terminology to define animal housing space generally falls into three categories: (1) species based – e.g., rodent housing, primate housing, canine/large animal housing, etc.; (2) use based – e.g., quarantine, postoperative care, etc.; and (3) management based – e.g., conventional, containment, barrier, and germ free. Terminology with regard to species- and use-based categories is self-evident, but the terminology used for the management-based categories is not universally defined. The following defines the terminology most commonly used today and employed in this book:

- *conventional* – standard housing systems for laboratory animals that do not offer the added level of control provided by barrier and containment systems;
- *containment* (keep in) – animal housing systems designed and managed to contain experimental or naturally occurring biological, chemical or radiation hazards in order to protect people, other animals, and the environment outside the containment area;
- *barrier* (keep out) – animal housing systems designed and managed to protect the animals from undesirable microbes coming from outside the barrier;
- *germ-free* – this is a highly specialized animal housing system managed to keep animals free of microbial agents; it is primarily an equipment-based technology, and is not covered in this book.

The last and only comprehensive book dedicated to the subject of planning and designing animal research facilities was edited by Theodorus Ruys in 1991. Since then there have been book chapters written on animal facility planning and design for laboratory animal science and medicine books, the most recent of which include Hessler and Höglund (2002), Hessler and Leary (2002) and Lipman (2007), and a review of the progress made in research animal facilities and equipment during the latter half of the twentieth century in a book published to celebrate the fiftieth anniversary of the American Association of Laboratory Animal Science (Hessler, 1999). In addition, there have been other publications by governmental organizations (Veterans Administration, 1993; CCAC, 2003; NIH, 2003) and numerous journal articles on the subject of animal facility design, including an entire issue of *Lab Animal* (Schub *et al*., 2001) and numerous articles in *Animal Lab News*.

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Section I

General Considerations

Chapter 1

Goals and Objectives for Research Animal Facilities

Jack R. Hessler and Steven L. Leary

I. Primary Objectives 3
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The ***goal*** for any animal research facility is to support research programs that promote the health and wellbeing of people and animals by facilitating high quality, scientifically sound research with animals.

Following is a short list of ***primary objectives*** that should be common to most research animal facilities. Additional objectives will likely apply to individual facilities.

I. PRIMARY OBJECTIVES:

- **Satisfy institutional needs** – Careful, detailed, upfront planning encompassing all phases of facility programming, planning, design, construction, and commissioning is required to assure that facility will function to effectively support the institution's research goals.
- **Comply with regulatory requirements** – Design and construction features along with operational procedure philosophy should meet all applicable codes and regulations. These include the *Guide for the Care and Use of Laboratory Animals* (ILAR,1996a), the Animal Welfare Act (AWA 1966), the *Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching (ILAR, 199bB)*, the CDC/NIH *Biosafety in Microbiological and Biomedical Laboratories* (BMBL, 2007), and state and local codes (NABR, 1991).
- **Meet the needs of the animal** – The facility must maintain the research animals free of disease, stress, and injury in a safe, comfortable, wholesome rich environment.
- **Provide environmental stability for the animals** – Uninterrupted maintenance of the animal's physical environment is essential. Maintenance of differential air pressures, in containment and barrier facilities is critical as is temperature, relative humidity and lighting in all animal rooms. Redundancy is required in the heating, ventilating, and air conditioning (HVAC) systems. Sufficient generator capacity should be available to maintain normal operation of the animal facility in the event of power outage or breakdown of mechanical systems.
- **Be operations friendly** – The ability to efficiently manage a facility is to a large extent reliant on facility design and equipment selection with a focus on optimizing routine operational procedures. Although good management can compensate somewhat, the price for poor facility design is usually inconsistent personnel performance and increased operating costs.

- **Be user friendly** – Sufficient procedure space must be available within the animal facility. The objective is to eliminate so much as practical the need to remove live animals from the animal facility to conduct the research. Operating policies typically preclude the return of rodents to the animal room once they are removed. For this reason, animal procedure space should be available, either within the rodent rooms or, preferably, in a connecting procedure room if the procedures can't be performed in the animal room. Some procedures require special equipment (e.g., imaging, irradiator) that may necessitate removal of animals from the animal room or even the animal facility. When special procedure space within the facility is impractical or unavailable, animals may be moved into a post-procedure isolation room. For species other than rodents, operating policies often preclude removing them from the facility for personnel health and public relations reasons, so adequate animal procedure space needs to be provided inside the animal facility. Having the animal facility in relatively close proximity to the research laboratories is a worthy goal, but need not necessarily be the overriding factor in determining the location of the animal facility.
- **Be maintenance friendly** – Facility maintenance requirements should be minimized so as to cause as little disruption of the animal environment as possible. Architectural materials and finishes must be durable under the environmental conditions to which they will be exposed. Engineering systems should be designed and selected to be dependable, easily maintained, and to minimize the need for maintenance staff to enter the animal facility.
- **Provide flexibility** – Facility design should be as flexible as possible to accommodate changing research objectives and species utilization while balancing the objectives of cost-effective construction and efficient facility management.
- **Provide security and effective operational control** – All facility access ports should be controlled utilizing automated technology, and preferably incorporating biometrics. Additional automated access control is highly desirable for specialized areas, e.g., large animal, barrier, containment, etc., and each animal room.
- **Employ sound occupational health and safety features** – A critical objective is to provide a safe and healthy working environment for personnel. Facility design and equipment selection should focus on: 1) Ergonomics to make animal care-related jobs safe and minimize repetitive injuries. 2) Minimizing exposure to animal related allergens and hazardous agents for personnel working with animals, animal waste, and animal care equipment. 3) Assuring that animal related allergens or hazardous agents present no health threat to other persons in the building, both inside and outside the animal facility.
- **Be cost-effective** –All design, material, and equipment decisions should focus on being cost-effective. To provide true value engineering all life cycle costs, including first costs, operational costs, and long-term maintenance costs should be considered.
- **Provide an aesthetic work environment** – Personnel should be provided with amenities that improve work environment quality and enhance recruitment and retention. Such amenities include adequate locker and shower facilities, pleasant break rooms (with windows if possible), quality training facilities, and attractive architectural finishes.

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Chapter 2

Master Planning and Animal Facility Location

Michele M. (Smith) Bailey and James Lew

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I. MASTER PLANNING

A. Rationale for Master Planning

When it is recognized that major changes need to be made to a program's animal facility or facilities, it is wise to look at the animal-care and -use program as a whole because animal facilities are not only expensive to operate; they are also among the most expensive research spaces to build or renovate. Does it make sense to do a major renovation of this facility? Are there other animal facilities that are under-utilized? Would it be less expensive and less disruptive to build a new facility and then move into it? Are there other animal facilities that will require major renovations in the near future? What is the direction of the animal-care and -use program – will more, or less, animal holding and procedure space be required in the future? Are there plans to utilize a different animal model that will require facility changes?

At many large institutions, there are multiple animal holding and procedure areas. Facilities may have been built over the years to accommodate a new need, or to accommodate the needs of a unit of the organization, without consideration of the whole. However, as facilities age, the smaller units may not have the resources or personnel to maintain these facilities appropriately. These facilities may not incorporate features required in a modern animal facility (such as appropriate security systems and monitoring, and environmental controls and monitoring) and they may not be able to support newer technologies – for example, intensive housing practices, such as mice in individually ventilated cages. This presents an opportunity to look at decentralized programs to see if operational efficiencies can be gained.

TABLE 2-1
Reasons to Have a Master Plan

Program is decentralized – maintenance and operational issues
Several facilities require upgrades in a similar time frame
Change in research focus
Change in animal use – change in animal numbers or models
Inability to adequately control environments
Change in animal caging sizes and types
Increased public accountability
Security
Regulatory pressures
To ensure future opportunities for growth are not excluded
To preserve real estate, infrastructure, resources for future applications
To model for phased expansion or consolidation of operations
To preserve the development of successful concepts and solutions

Master planning provides a chance to ensure that plans do not restrict future prospects for growth or expansion and helps in making wise choices regarding preserving appropriate real estate, infrastructure and resources for future needs, animal-facility related or otherwise (see Table 2-1).

B. Preparation for Master Planning

Before embarking on a master planning exercise, the goals, plans and objectives for the study must be clearly articulated. These goals, plans and objectives must be widely shared to make certain that there is concurrence to move forward (e.g., regulatory compliance, recruitment obligations, enrollment pressures, *per diem*s, pending research grants, budgetary commitments, fundraising, etc.). To be successful, there must be support from the institution's top administrators, an empowered champion of the project, and adequate resources allocated to carry out the study. Time must be invested with the participants in the master planning exercise and with those who will (or will possibly) be affected by its outcome, in order to ensure understanding of the need for a master plan and its goals, plans and objectives, and to secure agreement to proceed. Participants should include appropriate representatives with responsibility for facilities and finance from each affected subset of the institution, those who can speak for the long-term needs and the plans of each unit and validate projected animal census, physical plant personnel (planners, administrators), facility users, facility managers, and those with responsibility for the animal-care and -use program.

Applicable factors, standards and overarching pressures that can affect the outcome should ideally be recognized and understood at the start of the process. Institutional planners should provide site planning, zoning and infrastructure guidelines, and pedestrian, vehicular traffic and parking guidelines. Institutional specialists should provide guidance regarding animal facility standards, waste handling, biocontainment standards, and climatic and environmental issues. In addition, it is useful to understand state-of-the-art comparable facilities and related cost benchmarks to gauge the targets that should apply. Considerations can include circulation models (clean and soiled corridors), the use of modular holding "suites," inclusionary and exclusionary segregation techniques, cage and pen technologies (ventilated/isolation), the degree of automation, strategies for flexibility (the ability to exchange holding for procedure rooms or to reassign rooms to different species with minimal alterations) and adaptability (the ability to rearrange a given function within a room).

A suitable person from the institution, with the responsibility to ensure that the master plan is carried out in an appropriate and timely manner, must be provided with the appropriate authority and resources to accomplish the task and to manage the master planning project. It is generally wise also to engage the services of a proven consultant in animal facility master planning, from outside the institution, to participate in the exercise from the beginning. This will provide an unbiased, impartial facet to the study, to ensure that no single group's needs are perceived to be more influential than those of another group.

C. Steps to Master Planning

The master planning process can be broken down into manageable phases or steps. Initially, there needs to be an evaluation of the existing facilities to assess the status and condition of these facilities. This initial review need not be exhaustive, but should include a review of the building's functionality, occupancy and condition; its appropriateness for the planned use; the ability to ensure animal well-being – both behavioral and clinical; the appropriateness of surfaces and infrastructure for sanitation and disease control; the appropriateness of life safety and security measures; the ability of the heating, ventilation and air conditioning systems (HVAC) to adequately control the temperature and humidity; and the condition of the water system.

The planned use of the building must be considered to ensure that appropriate criteria are used in the evaluation – for example, is the facility intended for biomedical use, or for agricultural research and teaching? Appropriate standards should be applied, and may require blending of the guidelines (*Guide for the Care and Use of Laboratory Animals*, National Academy Press, 1996; *Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching*, 1999, Federation of Animal Science Societies), for example when using agricultural animals for projects that require neither the degree of environmental control of a biomedical research facility nor the expansive facilities of a normal farm setting.

After the initial evaluation, if a facility is deemed to be adequate for possible renovation, then a more detailed architectural and engineering evaluation should be carried out.

Simultaneously, the institution's short and long-term needs for animal use in research and teaching should be established. This can be done using an appropriate survey tool – a written survey, or meetings with the facility users and those with knowledge of the institution's future goals for animal-based research and teaching. Information should be obtained concerning the species to be used; the expected average daily census of the animals; the type of housing required; the number and type of procedure areas, specialized areas or equipment; the potential for sharing space; and the type and duration of the research and teaching.

It is important to have accurate, complete data regarding future needs. This will require tenacious follow-up with survey participants to ensure that information is gathered and interpreted correctly. Experience has shown the accuracy of census estimates for biomedical and behavioral research actually *decreases* as time horizons extend into the future. Estimates for 3–5 years hence tend to be more accurate than 10-year+ projections, as the investigator's funding and grant timeframes rarely extend beyond short-term horizons. Time commitments for near-term facility usage are generally well understood (e.g., 3 rooms are needed for the next 6 months out of 12), so diversification can be factored into near-term accommodation models; mid- to long-term usage can be more difficult to estimate as usage rates are often "worst-case scenarios" or are 100 percent additive without considering diversification. Accuracy can be reduced further for larger institutions with many investigators, as individual contingencies accumulate and magnify global estimates. On the other hand, teaching and instructional projections tend to be accurate for longer timeframes, as they're often based on managed growth in curriculum programs or planned enrollment strategies developed for years ahead.

Therefore, it will be necessary to assess the viability of using collected data at face value. Typically, census projections for biomedical research and behavioral studies are assignable at face value for up to a 5-year period; longer timeframes can be "reality factored" by allocating a percentage to future facility growth and expansion (e.g., provide for 50 percent of census growth for 10+ years and allocate the remaining 50 percent census growth into future facility expansion). Notwithstanding the above, each institution should develop its own process to evaluate collected data, based on the profile/number of respondents, its tolerance for risk and its comfort level with the accuracy of collected data.

From the survey data, an estimate of facility requirements can be developed. The needs articulated can be analyzed using standard planning models for calculation of space requirements. Typically, design consultants with relevant experience are employed to make the translation from census values to net assignable area, but benchmarks are available to gauge the extent of floor area required by species. Minimum area requirements per animal are established in regulations and guidelines; moreover, housing formats are standardized for smaller animals, such as mice and rats, so area assignments can be derived from cage and rack manufacturers' specifications.

One variable that should be defined at the onset is the typical census per cage, which will affect the density of animals in each room and often varies between institutions. As an example, current ventilated mice cages can accommodate up to 5 adults; however, it is typical to limit the census to 3 adults, providing a "diversified" occupancy rate over time (e.g., 160 ventilated cages per rack @ 3 mice/cage = 480 mice per rack; @ 5 mice/cage = 800 mice/rack, or a 67 percent increase). For example, a 30 ft × 20 ft animal holding room that accommodates eight 160-cage racks @ 3 mice/cage (480 mice/rack) results in a room census of 3840 mice or 0.16 sq. ft of room space per mouse – far less than the theoretical maximum of 6400 mice or 0.09 sq.ft. per mouse. Square-foot-per-animal assignments can be misleading as census numbers fall, but are useful for comparisons if baselines are similar.

Area assessments use *net assignable square footage (nasf)* as the basis for defining floor area requirements. Area calculations typically use the aggregate holding area nasf to estimate the required floor area. For biomedical research facilities with a census $>10{,}000$ mice, procedure rooms' net area can be assessed at 33 percent of total net holding areas; support spaces (cage-wash, lockers, etc.) can be assessed at 25 percent of net holding + procedure areas; and storage should be assessed at 15 percent of net holding + procedures areas (but seldom is). The aggregate of all net areas can then be multiplied by a "gross-up" factor to account for corridors, wall thicknesses and mechanical/plant rooms, thereby determining a gross floor area (gfa) for the building. Gross up factors are typically 1.9 to 2.25, depending on species, biocontainment levels and husbandry protocols. It is not unusual to have a gfa equal to twice the net assignable square footage.

The resulting data should be reviewed and validated by those who can speak for the long-term needs and the plans of each unit of the organization and the organization as a whole.

Once census and estimated floor area data have been validated and are considered to be accurate, a comparison can be made of the projected needs versus the condition and capacity of the current facilities. This comparison transitions the development of the master plan process into the subsequent "needs versus assets" exercise.

The next stage of master plan development typically entails three sequential steps:

1. Statement of user requirements
2. Accommodation analysis
3. Option development.

User requirements are established using the proposed census (once validated) to formulate a "high-level" summary of proposed programs/functions within the study's catchment area, identifying critical parameters such as maximum census at any one time, funding sources, investment strategies, risks/benefits, principal resources and key drivers. The endpoint is a

listing of proposed functions with approximate size (gfa) and relative ranking based on approved criteria (ranking of functions is often a challenge, but is highly recommended as it provides the basis for sequencing, deferrals and culling).

The accommodation analysis employs the user requirements as a "checklist" to compare proposed programs against available assets and existing resources; proposed functions are checked for their "fit" within existing buildings and infrastructure. The ability to house census, support procedures/equipment, process cage/rack cleaning, accommodate storage, achieve segregation and maintain correct environmental conditions is typically considered at this juncture. The objective is to assess the host location's ability to accommodate the proposed functions under a regime of full compliance with applicable guidelines and contemporary standards. The endpoint is typically an accommodation model with a "gap analysis" of facility shortfalls, which is carried forward in pursuit of asset/resource strategies that will support the proposed programs.

Option development builds on the previous two outputs to identify possible solutions that can accommodate the proposed program (s) in scope, sequence, and conformity with stated priorities (e.g. regulatory compliance, recruitment obligations, enrollment pressures, *per diem*s, pending research grants, budgetary commitments, fundraising, etc.) over an acceptable timeframe. Strategies that encourage functional "linkage," operational efficiencies and potential synergies between activities should be explored in detail at this juncture to capture the benefits of shared assets, diversification and common logistics. It is often useful to obtain assistance from design consultants in formulating options, as many non-operational factors affect opportunities (building codes/bylaws, infrastructure capacities, zoning, structural limitations, geotechnical conditions, etc.). The endpoint of this step should include a recommended approach that fulfills user requirements (through growth, upgrades or reduction/consolidation), incorporates implementation strategies that reflect financial capabilities and logistical challenges, and acknowledges the need for future change and growth. Options should be analyzed for suitability in the context of value to the institution, financial impact and operational considerations, with a preferred solution adopted as the "roadmap" for further development.

D. The Master Plan

Figure 2-1 depicts suggested major steps in the master planning process, some of which have already been discussed above.

When master planning, key strategies should be considered and incorporated, specific to the institution. These include the following:

- ensure that all animal facilities are in full compliance with standards;
- develop a limited number of centers of excellence for specific animal categories and investigator catchment areas;

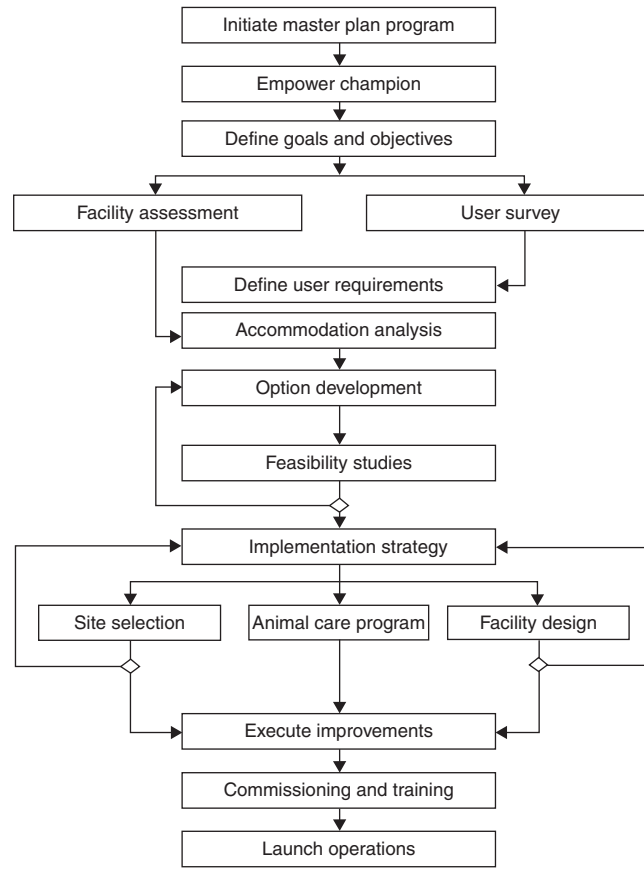

Fig. 2-1 Flowchart depicting suggested major steps included in a master planning process.

- build on successful and viable operations wherever possible;
- address the logistical needs of the user groups;
- decommission obsolete or unused facilities for reassignment to non-animal functions;
- ensure consistency of animal care across the institution;
- ensure that animal facility upgrades, renovations and new construction are coordinated to ensure operational efficiencies;
- focus on quality and economies of scale.

When the master plan options are laid out and a recommendation has been made, the rationale for the chosen option must be clearly articulated. This should include discussions on:

- initial capital costs;
- ongoing operation and maintenance costs;
- operational efficiencies;
- staff required;
- effects on *per diem* care rates;
- facility flexibility and adaptability for changing uses;
- effects on animal welfare, animal husbandry, veterinary care, and program oversight;

- the ability to control the animal environment (temperature, humidity, pressurization, and air changes);
- exclusion and inclusion barrier capabilities;
- biosafety issues;
- security measures;
- core services provided.

Reducing the number of vivaria will reduce the staff numbers required to carry out maintenance functions, animal care, housekeeping and material handling; reduce infrastructure and maintenance costs; reduce operational costs (such as heating and electricity) and the *per diem*s charged to investigators; increase the flexibility of facilities; maximize the use of the facilities; and encourage multidisciplinary, collaborative research.

However, most of the above are economic considerations versus programmatic needs – thus the importance of the next steps of stakeholder review and sanction, and the carrying out of specific feasibility studies.

E. Stakeholder Involvement

The key to the success of master planning is stakeholder involvement at every step along the way. The proposed master plan and justifications must be reviewed with the stakeholders. It is necessary to examine the overall picture to understand the ramifications of implementing the proposed master planning guidelines on associated research and teaching functions.

As important as the real and tangible economic persuasions are to the master plan, the needs of the stakeholders must be met. Consideration must be given to how critical the use of animals is to the program's goals and objectives, the intensity of animal use by the investigators (that is, the frequency with which the research demands attendance of the investigator at the animal facility), and the requirement (if any) for co-location of animal holding and procedure space with wet labs or other areas.

Although time consuming, it is necessary to have the master plan sanctioned by the stakeholders and senior administration, so that short-term decisions are made that support the long-term vision. For example, in an academic environment there may be open faculty meetings, and meetings with animal-care staff, with individual colleges, between colleges, and with senior administrators. It may be necessary to repeat the cycle of these meetings several times, to ensure full understanding of the plan and its potential consequences, and to achieve support for and concurrence with the plan.

It cannot be stressed enough that tangible support for the process from senior administration is critical. This support must be public and made known to the stakeholders.

F. Feasibility Studies

Once a master plan has been sanctioned, an in-depth feasibility study should be carried out to assess the scope, impact and significant aspects of the preferred option. This involves a thorough programmatic review and analysis of each phase of the plan to develop a practical working hypothesis and identify mitigating circumstances that may negate the viability of the option.

Issues studied should include the scope of work required to accommodate the necessary functionality, site context, accessibility/segregation issues, secure circulation and movement of personnel and materials; the status of the HVAC and building finishes (if a renovation); the availability of sanitization/sterilization equipment; the impact on the facility infrastructure/utilities; and the impact on the surrounding facilities, vehicular and pedestrian movement. Consultants are often employed to assist in the preparation of this type of analysis, unless sufficient in-house expertise exists.

The objective of this analysis is not to prepare a design for the execution of the plan, but instead act as a "reality check" to identify the critical issues, operational challenges, constructability, logistics and phasing/transition scenarios; to establish a most probable cost; and to develop a preliminary schedule for the implementation of the plan.

The feasibility study process should provide relevant information to facilitate the fundraising and execution of the master plan program, or it may require a re-evaluation of previous assumptions, as unforeseen conditions might necessitate reconsideration and modification of the master plan.

G. Implementation Strategies

Once the feasibility studies have confirmed the viability of the master plan hypothesis, it is important to focus on the implementation of the plan (or part thereof) as a separate step when moving forward (a master plan typically provides an overarching framework that covers many facets over a period of years; implementation should respond to conditions at the time of execution of a particular segment). The objective is to identify suitable strategies by understanding what will be affected and what will need to be triggered to achieve a successful outcome.

Implementation will depend on the scope of the program, the site context, the availability of funds, the impact on in-process work, and whether it is a renovation or new construction project. Often, multiple facility upgrades and/or new construction require sequential execution or phasing due to availability of funds and logistics. Major renovation projects in operational facilities will require transition plans with appropriate swing space for relocation of animals and procedures to another location during the construction.

This could trigger the need for enabling projects – for example, renovations at the short-term facility that could have strategic benefits in compliance with the master plan, or just be a cost center in the execution of the project. New construction will generally allow animals to remain in their current holding facility until construction and commissioning are complete.

Implementation options should be developed in concert with relevant stakeholders, administration, facility managers and physical plant services, etc., to obtain consensus or informed consent (depending on the culture of the organization), as the impact and interruptions due to work on the project could be significant. Once identified and sanctioned, the implementation plan should become part of the master plan framework for future reference and change control (often, recipients were not present at the time of planning, and documentation of intent becomes critical to maintain continuity of purpose and coordination).

H. Challenges and Frustrations

Getting agreement from the stakeholders for the master plan and/or implementation strategies is very challenging and time-consuming, but is necessary for success. Taking all the necessary time at this point can save much time later on, when delayed schedules can be very inconvenient or costly. It is frustrating to have a plan and then to determine that it is not feasible, due to unforeseen conditions. This requires an adjustment to the plan and renewing the cycle to get stakeholder agreement for the modified plan.

Challenges can differ depending on the type of institution. Academic institutions are generally slower to recognize the need for change; by and large, the pace is slower due to the necessity for wider consultation; there may be inadequate knowledge of national standards, which requires an education process; decisions often tend to be more democratic than autocratic; there is normally more decentralized control; there may be arguments for needing animals and laboratories in immediate adjacency to offices for academic needs; and pressures often exist for sites and infrastructure.

Industry often demands rapid shifts in plans due to initiatives not working out as forecasted, to new initiatives, and to mergers and acquisitions.

II. ANIMAL FACILITY LOCATIONS

There are many factors to be considered when deciding where to locate a vivarium. Asset strategies, financial expenditures, operational issues, security and constructability factors, and potential hazards and disasters all come into play, depending on the purpose and context of the proposed facility.

The value of a thorough site-selection process cannot be overstated. The time to evaluate site options is when strategic decisions are in play. Cursory site evaluations at an early stage may lead to the discovery of unanticipated (and often limiting) conditions later in the design stage or during construction. Changes to avoid limitations are unlikely at later stages, as leadership/focus has descended to the project level (now in tactical mode); revisions to designs may not be entertained as "project funding" is unavailable for this purpose, and will be seen as jeopardizing the success of those implementing the project. The result is often a loss of functionality for the duration of the facility's lifecycle due to a limiting project-based decision process.

The site-selection process is usually best served by starting with a clear definition of the functional program, stakeholder expectations for proximity/adjacencies (ranked according to priorities), an informed assessment of the candidate sites (including an investigation of context/infrastructure), defined financial capabilities, and knowledge of applicable regulatory requirements (codes, zoning, campus plan, etc.). Critical aspects of the project can then be framed into an evaluation matrix, with each option rated until a preferred solution emerges. This may sound like a simple process; however, experience has shown that this is rarely the case. While each situation is unique in purpose, context and process, the following themes are common to most situations.

1. *Renovate or build new?* While it may seem more practical to renovate an existing facility, there are important issues to be considered. Renovation is disruptive to others occupying the building. Such an approach may require a temporary move of animals/researcher/staff and then their subsequent return, with concomitant relocation expenses and research disruption. Although usually thought to be less expensive, the limitations and unforeseen conditions associated with renovation often drive the cost up while facility design solutions are constrained by the existing building structure. New construction allows continuation of the research in the existing spaces; and may provide more opportunity for expansion, optimization of the design for operational efficiencies, future flexibility, different levels of biocontainment, and new methods of housing animals. However, new construction may not be possible due to lack of developable space or higher priorities for that space. Careful analysis is often required to establish the "big picture" in terms of cost and opportunity, to determine the best value.
2. *Separate animal facility or integration into a mixed-use building?* A vivarium can stand alone as an independent facility or be included as part of a larger building; both approaches have been successfully executed – the correct solution usually depends on the program, required connectivity and budget. A smaller vivarium may be preferred when connected to research and teaching spaces for convenient access; a larger vivarium may require a building of its own due to its sheer size or the need for future horizontal expansion. A larger floor plate usually provides an opportunity to have the vivarium occupy a single contiguous floor (very desirable for efficient handling of materials), even if on the basement level, with office, research, laboratory or teaching spaces above. Multiple animal sites within a single campus setting require a duplication of costly support and washing facilities, which suggests

that consolidation may be a more cost-effective approach from an animal-care perspective (but may not be feasible due to the dispersion of client research activities). Critical requirements in a co-location situation include: a continuous physical separation along the interface with other occupancies; separate/controlled access for personnel, materials and animals; dedicated HVAC and controls systems; and appropriate locations of intake and exhaust systems. Every situation merits a thorough analysis of the pros and cons of independent versus co-located animal functions.

3. *Contexts and adjacencies*. Consideration must be given to the context and adjacencies surrounding a vivarium. Where does it make the most sense programmatically to locate the facility? Where will the most stakeholders have adjacency? Will animals transit between holding and research areas? Critical site requirements include sufficient space to accommodate a clean and soiled circulation system (which can require greater floor plate depth and/or multiple elevators); direct/secure vehicular access for deliveries of animals, materials and removal of waste; and sufficient real estate to accommodate future growth and expansion. Inappropriate adjacencies such as cafeterias and public assembly spaces, or noisy functions such as maintenance shops, should be avoided. Care should be taken to assess the impact of airborne emissions from the vivarium exhaust systems and emergency generators into the surroundings, as well as the risk of re-entrainment and ingestion of contaminated air from surrounding buildings into the vivarium air supply. Wind-tunnel and building envelope studies are typically employed during the design phase to determine the best solutions within the given context.
4. *Security*. This is an ever-increasing consideration when siting a vivarium. Interestingly, security experts suggest that the most vulnerable stage of an animal project is often during its construction stage; secure conditions with continuous surveillance during construction can be obligatory. General wisdom suggests that an animal building should complement adjacent buildings and be without features that emphasize the occupants or provide opportunities to view the activities within. The immediate perimeter should be easily visible, and free of dense landscaping that could hide suspicious packages. Doorways and access paths should be clear and well illuminated at all times. Adjacent roadways and parking lots should be at a safe distance away from the vivarium perimeter to minimize the risk of intentional or accidental car/truck impacts and explosions (for this reason, a vivarium shouldn't have unrelated parking garages below). Security should always be considered in site selection, as it will no doubt escalate in importance over time.
5. *Access and egress*. Routing of authorized personnel and vehicles should be for the exclusive use of vivarium activities (shared circulation with non-vivarium functions, if necessary, can raise the complexity of security controls and increase the burden on surveillance systems). The facility must be easily accessible for the users of the facility and animal-care staff. Adequate parking should be available, particularly if a centralized model is chosen, where researchers may be required to shuttle back and forth between vivarium, laboratories and their offices. Adequate maneuvering and parking space should be provided for clean and dirty loading docks, waste pick-up and laundry service (if applicable), with accommodation for various-sized delivery vehicles. Special attention should be given to providing parking and direct service access to mechanical, electrical and plant-room spaces from the exterior (for service and maintenance purposes) without the need to enter into the vivarium.
6. *Utilities*. Animal facilities require reliable and consistent performance from the utilities to support their 24/7 operations. In some circumstances, multiple connections from different sources or utility grids may be warranted for critical installations. The availability of adequate, dependable infrastructure connections and utility capacities (sanitary sewers, domestic and fire protection water supply, chilled water, plant steam, electrical supply, data/communications, etc.), often with redundant back-up, are not insignificant considerations in site selection, and have been responsible for the elimination of otherwise ideal locations due to the prohibitive costs associated with infrastructure modifications. The assessment of utility locations and capacities should also be included for potential future growth and expansion.

Chapter 3

A Team Process from Programming to Commissioning

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I. INTRODUCTION

The architectural design process follows a number of phases or stages, which result in the production of a variety of documents along the way. Although this process can vary greatly from project to project pending the delivery strategy and facility requirements, for the purposes of this book we will describe a more traditional approach.

The design team can be quite large, and often encompasses a wide variety of architects, engineers, planners, consultants, users, administration and facilities, and the owner's operations staff. They each have their own set of goals and objectives and thoughts about a given project. It is the goal of the team to assemble this information into a cohesive set of criteria so that everyone on the team is engaged in the same way for the same objective. The actual process can be divided into the following traditional phases: programming, schematic design, design development, construction documents, bidding and construction, and commissioning.

II. PROGRAMMING

Programming is one of the most important activities in development of a new facility. This phase establishes the foundation upon which all planning, design and construction will rely. The programming effort should refine and clearly state the goals of the project. As the name implies, programming involves qualitative and quantitative descriptions of the programs and activities that need to be supported by the new

facility. The program will define what goes into the facility, including many design features, so planners experienced in the design of animal research support facilities are a must.

Information is gathered from the governing agencies and authorities having jurisdiction, such as zoning, planning, building and engineering. Concurrently, information is gathered from the institution or company itself that would affect the design and function of the facility. Often, institutions and companies have internal requirements for space allocations, engineering and architectural criteria, and specifications for materials used in construction. Information is also gathered from the administration that would outline the research and program needs, including any budget limitations. The design team will meet with the representatives of the institution/company to create a set of requirements and criteria for the facility. These representatives would include animal facility management, investigative staff, department chairs, administration and facilities. It is very important that the stakeholders from the facility engage in this process and dedicate time to these meetings. Meetings could occur every 2–3 weeks and last several days, depending upon the size and complexity of the project. The programming document should provide a detailed description of the attributes and capabilities that the new facility must have to support the institutional requirements.

This effort starts with understanding the species to be housed, the quantity of cages or animals, housing choices and type of research to be completed, and will result in a comprehensive list of functional rooms that the facility will need, such as holding, procedure, cage-wash, docks, offices, etc. This will result in a written program (list) of spaces with total net square feet (nsf). In addition to these spaces, the design team will identify other spaces, such as toilets, mechanical rooms, electrical rooms, shafts, etc., that are required. Room data sheets are created at this phase to document the physical criteria for each room. Often there is a written summary of each room type that describes the criteria and requirements, and the relationships of the spaces and how they interact with each other. Flow diagrams are created to examine adjacencies, relationships, and locations relative to flows within the facility. These are done for animals, personnel and equipment. At this phase a preliminary budget is usually established, along with the anticipated schedule to prepare the documents, construct the building, and allow for move-in and occupancy of the finished project. It is important that enough time be allowed for this phase, as it sets the scope of work for the rest of the project. Large changes can still be considered at this early stage that affect the scope of work, and which can't be done in later stages without serious impacts to the project budget or schedule. It is critical that the stakeholders review these documents and provide comments and approval prior to moving into the next phase of design. It becomes increasingly harder to make adjustments to the project as each phase gets approved.

III. SCHEMATIC DESIGN

Using information gathered during the programming phase, conceptual or schematic design(s) are prepared. The design team will prepare floor plans (including options), building exterior elevations, and general layouts of major engineering systems, to confirm the function of the building and how it will integrate into the existing site and context of buildings. The building structural system and grids are established at this time. As schematic design takes form, it is regularly examined in relation to the program, schedule and budget to insure compliance, and modified as required. A Basis of Design (BOD) document is produced which includes the project goals and objectives, program, room data sheets, code review, blocking/stacking diagrams, building systems descriptions, and all drawings. This serves as the roadmap for all team members as the project moves forward. Meetings during this phase will continue to be every 2–3 weeks, and, depending upon the complexity of the project, of several days duration. The project may be estimated again, and adjustments to the design made if required to meet the budget requirements.

IV. DESIGN DEVELOPMENT

In this phase the design is further developed in detail. The structure is developed, confirming beam and column sizes. Typical building components are addressed so that all aspects of the construction are identified. The exterior enclosure is designed and documented with elevations of the exterior, typical wall sections, and details. Materials and methods of construction are chosen and documented. Building sections are drawn to illustrate the structure and spatial relationships, and to understand the general construction. The major mechanical, electrical and plumbing systems of the building are documented in principle so that all major mechanical spaces are identified, equipment is located, and the distribution of these systems will work. Interior finishes and design are developed. All major research equipment is located. Typical hardware sets and door operations are identified, and typical ceiling plans are developed. The site plan is developed, showing entryways, parking areas, and access from the street. As the design development takes form, it is regularly examined with all project stakeholders in relation to the program, schedule and budget to insure compliance, or to see if any modifications are needed. All design disciplines are coordinated with each other. A preliminary set of specifications is usually developed which outline the installation, type and quality of materials selected for the project. Although it is unusual for the stakeholders to review the specifications, the design team should present the specification information. This is the last phase where changes can be made without major compromise to the project in one way or another, so it is imperative that the stakeholders review

and sign-off on the design and details at this stage. From this point forward the project moves into a documentation phase, whereby changes have profound impacts on the project. Meetings during this phase will continue to take place regularly and can be very lengthy, given the amount of detail to review.

The project may be estimated again, and if the cost exceeds the budget the administration may institute a value engineering session to bring the project back into budget. These sessions should be attended by the stakeholders, as value engineering choices can affect operational cost, quality of materials, and functionality.

V. CONSTRUCTION DOCUMENTS

During this phase the project is completely documented with a set of construction documents. This is the longest and most intensive phase in the process. All design decisions should have been made by the start of this phase, so there may only be a few meetings to review special or unique details. Drawings are dimensioned, noted and detailed, with references to details and specifications as required, and any outstanding issues are finalized. Final specifications for the materials and standards of construction are prepared. All the drawings and specifications are checked and coordinated to ensure that the project will be as correct as possible and has the necessary information for the successful completion of the construction. As the construction documents take form, they are regularly examined in relation to the program, schedule and budget to insure compliance, or to see if any modifications are needed.

Upon completion, the construction documents are submitted to the appropriate building officials for the purpose of obtaining a building permit. The project is often estimated for the final time, and final adjustments are made to the drawings. This may require another VE session, or alternative bidding strategies to be developed to make sure the project is on budget.

VI. BIDDING AND CONSTRUCTION

Drawings can be prepared for the bidder after completion of the permit processing or, more likely, during the time the building department is examining documents. Bid documents included all of the construction documents, instructions to bidders, general conditions, and other documents required to execute the project. There is generally a specific number of bidders, although for public work all qualified bidders are accepted. There are several methods of bidding and contracting; the two most common are *general contractor hard bid*, or *construction management* – which in itself has a diverse methodology of bidding. The most important thing for the stakeholders is to stay involved in the project during both the bidding and construction stages. Two aspects of involvement would be to review any substitutions of vivaria-related equipment and materials, and to attend the final walkthrough of the building. Substitution requests may need to be reviewed by the owner when it is determined that they will affect the budget or schedule, or the appearance or functionality of the finished building. The design team will periodically review the construction to ensure it complies with the construction documentation. At the end of the project, the design team will conduct a final "punch list" for the project. Often the owner attends these reviews, which can prove valuable and educational.

VII. COMMISSIONING

Although it is worth a book on its own, owners should entertain the requirement to commission the facility. This can be done by an outside agent or by the design team. Given the complexity of vivaria design and the building systems, getting the building systems started up correctly and ensuring that they function as designed is extremely important prior to moving animals into the building (see Chapter 5 in this book).

VIII. SUMMARY

The most important thing to understand about the design of animal facilities is that a team approach to design will result in a better facility. This team comprises a variety of members, including programmers, architects, engineers, owners, users and constructors. We should underscore the strong desire to include consultants with a great deal of experience in this field, since these are very unique facilities with special requirements. Successfully designed animal facilities are typically the result of a collaborative approach of all the team members.

Chapter 4

The Planning, Design and Construction Process

John N. Norton and Alex B. Brouwer

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In order to design a new facility with appropriate materials and functionality, the *NIH Design Policy and Guidelines* (NIH, 2003) and latest edition of the *Guide for the Care and Use of Laboratory Animals* (ILAR, 1996) are essential reference documents. These documents, in conjunction with numerous publications and conferences, provide design standards and technical criteria that are useful in the construction of animal research facilities (Hessler and Moreland, 1984; Ruys, 1991a; CCAC, 1993; Hessler *et al*., 1999; Rahija, 1999; Hessler and Höglund, 2002; Hessler and Leary, 2002). The design team must know how to interpret not only the information within the documents, but also the intent as it relates to the construction

project. This chapter describes the design process from conceptual design through all phases of engineering and construction of new facilities (Cole, 1991). Design issues and potential pitfalls are described.

I. TYPICAL PROJECT STEPS

The eight steps listed below outline the major activities in the design of an animal facility. The duration of each step and the total project is dependent on its scope and size. A suggested schedule for each of these steps is shown in Figure 4-1.

1. Programming and planning/master planning
2. Schematic design
3. Design development (sometimes referred to as preliminary design)
4. Construction documents preparation
5. Bidding and construction contract award
6. Construction phase
7. Commissioning
8. Validation

1. *The Project Team*

Planning for new or expanded facilities usually results from programmatic requirements. Forces impacting these requirements may be growth of existing programs and research staff, changes or additions to programs, changing science, needs for greater efficiency, and more sophisticated capability.

The impetus for new or improved facilities may come from any of the constituencies served by the facilities. Institutions also may have strategic plans to meet research needs based on projected growth and activities. However, it is most likely that changing requirements for animal facilities, such as the need for more space, develop over time, and prompt a planning process. Generally, the executive officer or senior administrators of the institution, when made aware of the situation, take the lead in the process, and appoint a planning group made up of senior staff with interests and responsibilities for research support facilities.

When starting a new facility, it is important to assemble the right project team and to establish the design parameters. Knowledgeable and experienced members are essential. The typical project team (Figure 4-2) consists of an owner representative, facility user representatives and technical consultants. Institutional members may include representatives from facility management, animal care, research administration, employee health, research scientists and security. The members of the project team should be selected for their insight, their ability to identify and overcome issues, and their willingness to commit considerable time to planning meetings and related project activities. They must also be aware of their responsibility to fairly represent the requirements of their constituencies.

2. *The Kick-Off Meeting*

The senior administrator with responsibility for research support facilities will initiate the process by calling a kick-off meeting of the project team. The first step in the planning process is to define the needs that initiated the planning process. A clear vision on what is to be accomplished with the new facilities is essential. Other issues on the agenda for this meeting are project parameters, project goals, project schedule and project budget.

The project team leader should be clearly identified during the kick-off meeting. Typically, the leader on the client side is a project manager, who is a representative of the facility's engineering group or the building manager. The consultant planning firm or the architectural engineering (AE) firm typically has a project manager involved from beginning to end of the design effort (Somin and Wilson-Sanders, 2004a).

A. Programming and Planning

At the start of the project, a preliminary project scope (e.g., square feet, number of storeys, etc.) and the ultimate project budget parameters should be defined (Tyson and Corey, 1999). In some cases, the project cost parameters are not defined until after initial conceptual planning and design is completed. This, in effect, can make the schematic design phase more complex because, when "the sky's the limit" in terms of needs assessment and conceptual design, the proposed result without budgetary constraints can be excessive. Typically, the design drivers are quantified during an interactive programming process of interviews, surveys, benchmarking and planning meetings with the user representatives (see sections below). The consultant/AE project planner and project manager will systematically interview the user groups to identify and prioritize the issues, which will ultimately dictate the design. A series of routine planning meetings are held to review the findings with the planning team. The priorities are reviewed before alternative building concepts are drawn and presented to the planning team.

The AE firm chosen to "program" the facility may be the same or a separate firm that was selected to design the facility. Programming is one of the most important activities in the development of a new facility. The program will define the components of the facility, including many design features, so the planners of the AE firm must be experienced in the design of animal facilities.

A clear vision on what is to be accomplished with the new facilities is essential. This may be facilitated by tabulation of current operations: size of staff, number and types of research programs, numbers and species of animals maintained, husbandry practices (including animal housing systems) and current facilities. A review of space utilization may be useful, including listing all spaces by area and function, taking account of special activities such as research or procedure space for behavioral studies or hazard containment. This should provide a snapshot in time of current activity and resources.

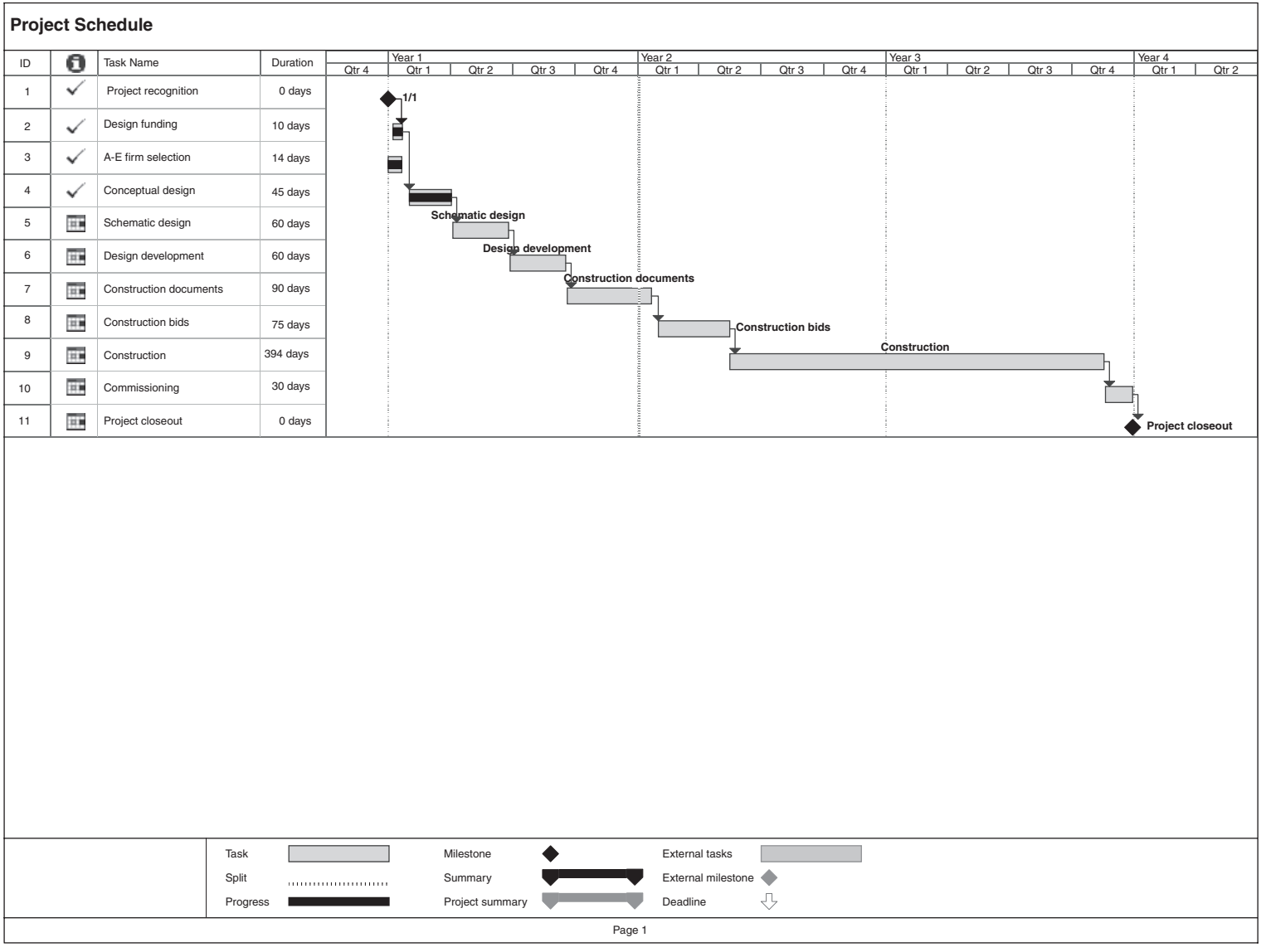


Fig. 4-1 Typical design and construction schedule for a new animal facility.

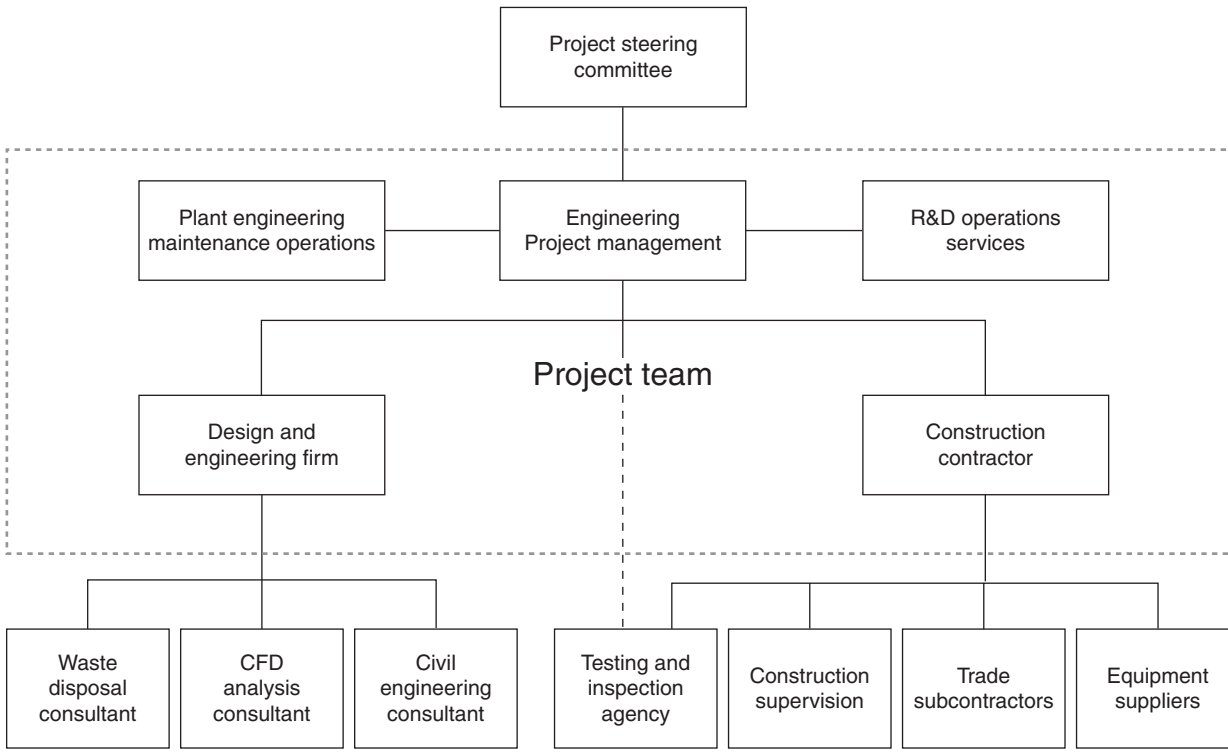


Fig. 4-2 Project team organization for a new vivarium.

Considerations should also include peak activities. Undoubtedly the plans will involve meeting needs at the present time, but also for years to come. The institutional planning group members will provide much of the information regarding the current status. Interviews with key staff members should provide information pertinent to predicting future animal facility needs.

As the name implies, programming involves qualitative and quantitative descriptions of the programs and activities that need to be supported by the new facility. Programming should provide a detailed description of the attributes and capabilities that the new facility must have to support these activities. It should list all of the kinds, numbers and areas of spaces required, such as:

animal rooms	procedure rooms	special labs
surgery suite	imaging	pathology/necropsy labs
containment	quarantine	barriers
administrative space	facility offices	conference room
lockers/toilet/showers	break room	food preparation
general food storage	refrigerated food storage	bedding storage
general supply storage	chemical storage	cage repair
receiving	cage-wash, clean	cage-wash, soiled
clean cage holding	general waste holding	refrigerated waste holding

Functional adjacencies, including animal rooms and procedural areas, should be described and include staffing projections. Code issues, site conditions, mechanical, electrical and plumbing systems, architectural finishes and fixed equipment should be addressed. Finally, the program report should provide a detailed budget with a construction schedule.

One of the questions typically raised during the early stages of a project is, how much net animal holding space is achievable? The size of the animal facility with regard to meeting current activities and for the future is a critical issue, with no simple answer or method to determine it. Obviously, the kinds and numbers of animals to be maintained, the kinds and numbers of research programs and the number of researchers affect the equation. There has been a trend to limit movement of animals from animal facilities and to incorporate additional procedure space, ranging up to 25 percent or more of the animal holding space. This may be especially important for facilities that are stand-alone and not located in laboratory buildings. Several methods can be used to get an approximation of the space required; these include the following.

1. *Percentage of research building*. Empirically, it has been found that large biomedical research buildings require 10–20 percent of laboratory space that functions as animal facilities.
2. *Animal number*. If the species of animals and the number of each that must be maintained are known, the space for animal housing can be calculated. Using the average of 40–60 percent for net to gross relationships, the size of the animal facility can be estimated.
3. *Historical*. Previous experience and historical data for the institution may be helpful in predicting future needs. Use of multiple methods may be reassuring if they come up

INTERVIEW QUESTIONS

Group: **Date:**

PARTICIPANT Names:

	CURRENT	PROJECTED
Staffing		
• FTE		
• Other		
Animal housing		
• By species		
• Quarantine		
• On study		
• Unique requirements		
Space needs		
• Animal procedure space		
• Laboratory space		
• Research support space		
• Major equipment		
• Module preference		
• Engineered systems		
• Adjacency requirements		
Support facilities		
• Dedicated		
• Shared		
Design issues		
Preferences		

Fig. 4-3 Sample list of interview questions.

with similar results; if they don't agree, this may be a reason to analyze the need further.

After development of the building program – a document that summarizes square foot requirements, animal population and staffing requirements, work-flow diagrams and general design requirements – building concepts are developed which graphically take the information from the building program and incorporate it into a building block or plan view for review with the planning team (Tyson and Corey, 1999). Building concepts for review may include single- or multi-storey buildings, single- or dual-corridor buildings, and buildings that segregate animal species by type or by room size.

1. *Interviews and Surveys*

As noted above, interviews and surveys are used to gather programming and planning information from user groups. This structured process involves coordination preparation, information gathering, analysis and reporting.

Interviews and surveys are typically conducted by the architect or planner following a previously agreed list of questions and subjects for discussion (Figure 4-3). It is important to allow some interaction during the interview process. The architect or planner must also document the responses and provide an opportunity for interviewees to review and clarify their responses.

PLANNING ISSUES 1

Operational:

- Quarantining duration and location (90 days vs 60 days vs off-site)
- Group housing vs pair housing vs single housing for primates and canines
- Multiple studies in single rooms vs dedicated rooms
- Enrichment caging vs larger pens
- Ventilated caging phase-in
- Breeding colonies phase-in
- Increased in-house long-term studies
- New World vs Old World primates
- Impact of "tissue from external sources"

PLANNING ISSUES 2

Support facilities:

- Automated bedding dispensing
- Bedding disposal issues
- Carcass disposal
- Cage sanitation methods
- BL-2 vs BL-3 level upgrade-ability
- On-site path lab
- Off-site histo processing
- Potential PCR or ultrasound facility
- Provision for visiting scientists

PLANNING ISSUES 3

Space:

- Dedicated large animal quarantining vs "available room"
- 85% optimum utilization vs 90%
- 14 × 25 room module vs 12 × 25 with trenches
- 30" × 71" size caging vs 30" × 49"
- Census ratio:

	Rabbits	Monkeys	Rats	Guinea Pigs	Cats
Current #	×××	×××	×××	×××	×××
Current %	50%	14.5%	28.3%	5.8%	1.4%

- 10% "shell space" provision
- Corporate directive for "increased in-vitro tox studies"

PLANNING ISSUES 4

Engineered Systems:

- Animal holding rooms to be - -
- Procedure rooms to be + +
- Ventilated caging phase-in
- Decontamination/autoclaving procedures
- Telemetry provisions
- House vacuum system
- Gas detection system
- RO water system for animals
- Chilled water plant capacity
- Caging orientation within rooms

Fig. 4-4 Sample list of planning issues, determined from interviews.

While some organizations feel it is important to allow everyone involved in the design and engineering process an opportunity to participate, most organizations will limit the level of involvement to certain management and supervisory groups. Consultation with department heads and senior institutional officials may be necessary to obtain information on plans for new activities, program growth and staff recruitment. Research groups with special needs should also be included. On an average sized project, 20–50 people should be surveyed and/or interviewed. Typically interviews are scheduled for hourly sessions, and it may take several weeks to complete the process for an entire client base.

a. Interview and Survey Findings

Interview and survey findings should be documented in meeting notes and/or summaries. Issues raised from the interviews should be prioritized on an issue list for referencing (Figure 4-4). Layout-related survey findings should be summarized in a graphic format.

b. How to Interpret Survey Findings

Surveys are most useful in establishing the size of spaces and support facilities. The building users are most familiar

with bottlenecks and operational issues that need to be addressed; therefore, it is important that the survey findings be carefully reviewed by the planning team and the operational management of the facility.

2. *Benchmarking*

Institutions that have similar missions, with reputations for state-of-the-art animal facilities, may be contacted and visited to provide a standard against which the proposed facility can be assessed. Visits to "benchmark facilities" may provide innovative ideas and information on facility design, equipment, construction and operations. To begin the process, determine what is being benchmarked, and start as early as possible in the planning process.

The typical benchmarking team should consist of an animal husbandry representative (supervisory or managerial), a veterinarian and a technical representative (engineer or planner).

a. Where to Benchmark

There is a great diversity of animal facilities across different geographical regions. When identifying facilities to benchmark, those that are most similar to the planned project should be selected, and those that have significant operating experience (i.e., that have been in operation more than a year). Additionally, varying the geographic location of facilities to benchmark may provide more diverse design features and associated operating experiences.

b. How to Benchmark

It may be helpful in the benchmarking process to make a list of comparative data that you wish to obtain, such as operating data, building materials, cost of construction, and room finishes (Figure 4-5). This information can be included in the benchmarking questionnaire sent in advance to the facility that will be assessed. While benchmarking facilities may be done via the Internet, a 1-day visit to the institutions of interest is usually much more productive.

c. Benchmarking Findings

The benchmarking team should document its findings in a site visit report, and provide some analysis and conclusions in written form to share with the design team.

Many benchmarking findings, such as animal housing standards and room sizing, can be documented in tabular form. Other findings, such as project justification, operational provisions and procedures, are more subjective, and can be addressed in narrative form to convey variations between benchmarked facilities.

Benchmarking checklist		
DATA		facility size
		year constructed
		# floors
		floor-to-floor height
		animal room sizes
CENSUS		species
		quarantine
		housing
		staff
COST		construction cost/sf
		operating cost/y
		equipment
		other
VISIT OBSERVATIONS		operational issues
		positive features
		negative features
		other

Fig. 4-5 Checklist for benchmarking similar facilities.

	MINIMUM SIZE
Core functions	
– Holding rooms	15×20
– Anterooms	10×20
– Incoming quarantine	20×40
– Receiving/shipping dock	20×70
AR support functions	
– Treatment room/laboratory	20×30
– Feed storage	20×15
– Supplies-storage	10×20
– Cage-wash	30×50
– Waste handling dock	10×20
– Transport cage/equipment storage/repair	20×25
Staff support functions	
– Entrance vestibule	10×10
– Toilets/lockers/showers	2@10×25
– Offices	10×15
– Workstations	8×8
– Conference room/training/breakroom	20×20
– Records storage	10×10
– Office supplies storage	10×10
Building support functions	
– Mechanical room/mechanical penthouse	50×300
– Electrical/data/communications rooms	20×50
– Housekeeping closets	8×10

Fig. 4-6 List of basic functions and minimum sizes.

3. *Space Guidelines*

The data gathered from the interview, survey and benchmarking processes help to outline the space guidelines for holding rooms, procedure rooms and support spaces in a new facility (Figure 4-6).

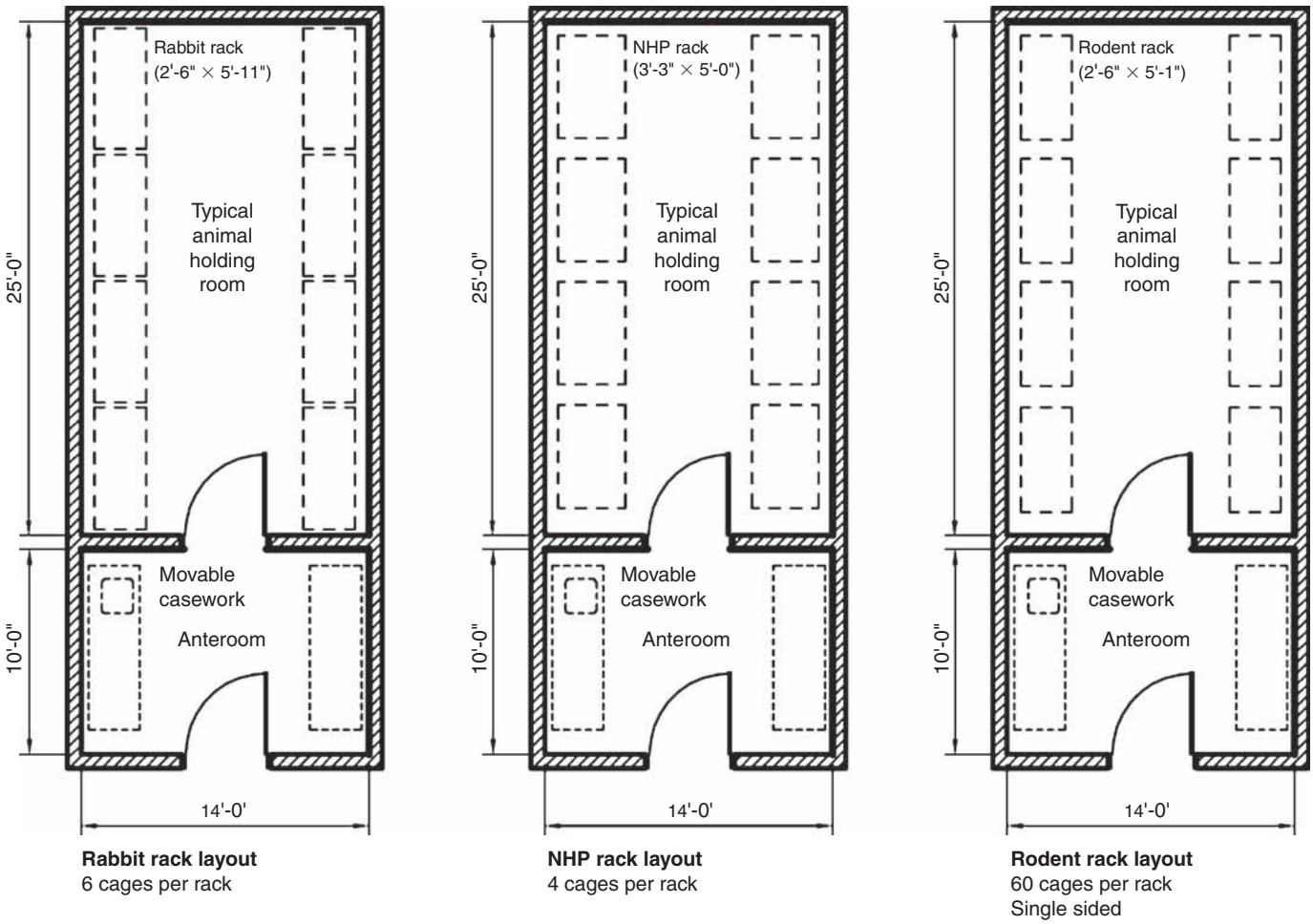


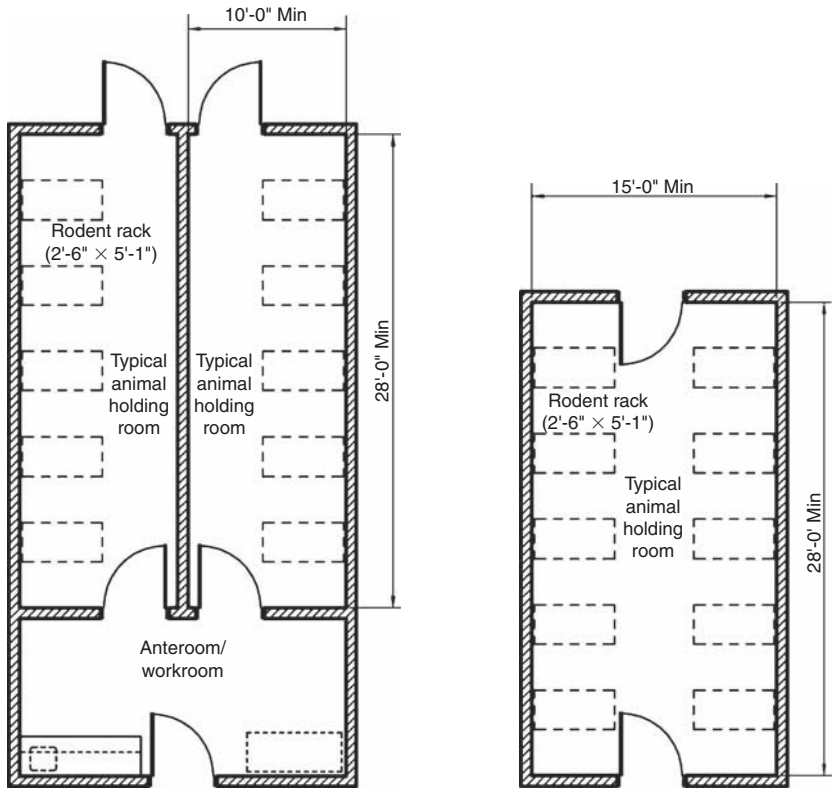
Fig. 4-7 Multi-species room diagrams.

a. Holding Rooms

Animal holding rooms comprise much of the space in animal facilities, often 50 percent or more of the program space, and they may be the most numerous kind of room in a facility. Individual rooms, or suites of such rooms, may determine the building column arrangement and support structure in an independent animal facility. Often, animal facilities are part of laboratory buildings, and column spacing is dictated by the size of the laboratories. The column spacing may influence the dimensions of the animal rooms. When possible, generic animal room sizes or modules may be utilized to minimize design and construction costs, to provide standardization and orderliness, and to facilitate flexibility (Ruys, 1991b; NIH, 2003) (Figure 4-7). The species of animals to be maintained, the type of cages to be used and the activities to be conducted will have a great deal to do with room layouts and dimensions.

Critical decisions regarding the design of holding rooms and resulting floor plans of the building should be made early in the planning process. Facilities may be designed around dedicated room layouts associated with specific species such as rodents, rabbits, non-human primates or canines. Small rooms are researcher-friendly, but have a relatively low cage density per square foot. Larger rooms provide more flexibility and are more efficient for high cage density per unit of area.

Room configurations must accommodate the research and animal care activity, as well as efficiently provide space for animal housing. In addition, planned sanitation practices will greatly influence the layout of holding rooms. The design team should consider the frequency of room sanitation and the exact provisions to be incorporated in the holding room. There are many different philosophies currently being practiced regarding room sanitation. These range from the use of completely portable equipment, normally kept outside of the room, to rooms that are "self-cleaning," with built-in flushing systems, trenches with floor drains, hose-down systems and hand-washing sinks. The provisions to the room may vary between species to be housed and should be discussed specifically for each room type, so that the designers can provide for equipment such as service sinks, hose racks and detergent dispensing



Option A
750 Rodents per room
0.593 sq. ft Per rodent

Option B
1500 Rodents per room
0.316 sq. ft Per primate

Fig. 4-8 Rodent room diagrams for two-sided racks.

panels as required. Depending on the species and the nature of the work, fixed or portable hand-washing sinks should be provided in adequate numbers.

Reducing workspace in the rooms to increase cage density per square foot of floor area may actually reduce efficiency and make the rooms difficult places in which to work. Different room configurations have advantages and limitations, and there is no one best size or way to configure them. During this early design stage, it is easy to become overwhelmed by detail. Remember to consider the big picture by making sure that space is allotted to provide support functions for each room.

Holding rooms designed for a defined species should be modeled for size based on specific rack types. If the building is planned for multiple species to be held in a single room design, the room size needs to be developed and tested for multiple types and sizes of racks or rack configurations before a building layout is attempted. Since there is a multitude of rack types on the market, it is important that the planning team considers alternatives available based on current use of the facility as well as the future use as it relates to species.

The rack orientation relative to the side walls will also affect room size and configuration. Many narrow rooms lend themselves best to single sided racks, which are parallel to the room walls. Double-sided racks may be best located perpendicular to the side walls, leading to wider room designs (Figure 4-8). This becomes even more critical if aisle spacing is considered. Typically, aisle spacing between parallel racks should never be less than 30″ to keep animal care personnel from bumping into racks behind them as they are working with a specific animal cage. In a room with racks that are oriented perpendicular to the length of the room, a central aisle that accommodates cart traffic, as well as movement in and out of the room, is typically spaced 4–6 feet, at no less than 36″ clear.

The ideal holding room layout(s) can be modeled during planning sessions with a simple planning kit of scale parts (cut outs) or by employing a 3D computer aided design (CAD) program, as used by most planning consultants and AE firms. Figures 4-9 and 4-10 illustrate examples of different designs.

b. Procedure Space

Procedure requirements for different species vary significantly. In certain instances the planning team may conclude that some procedures can be done inside the holding room

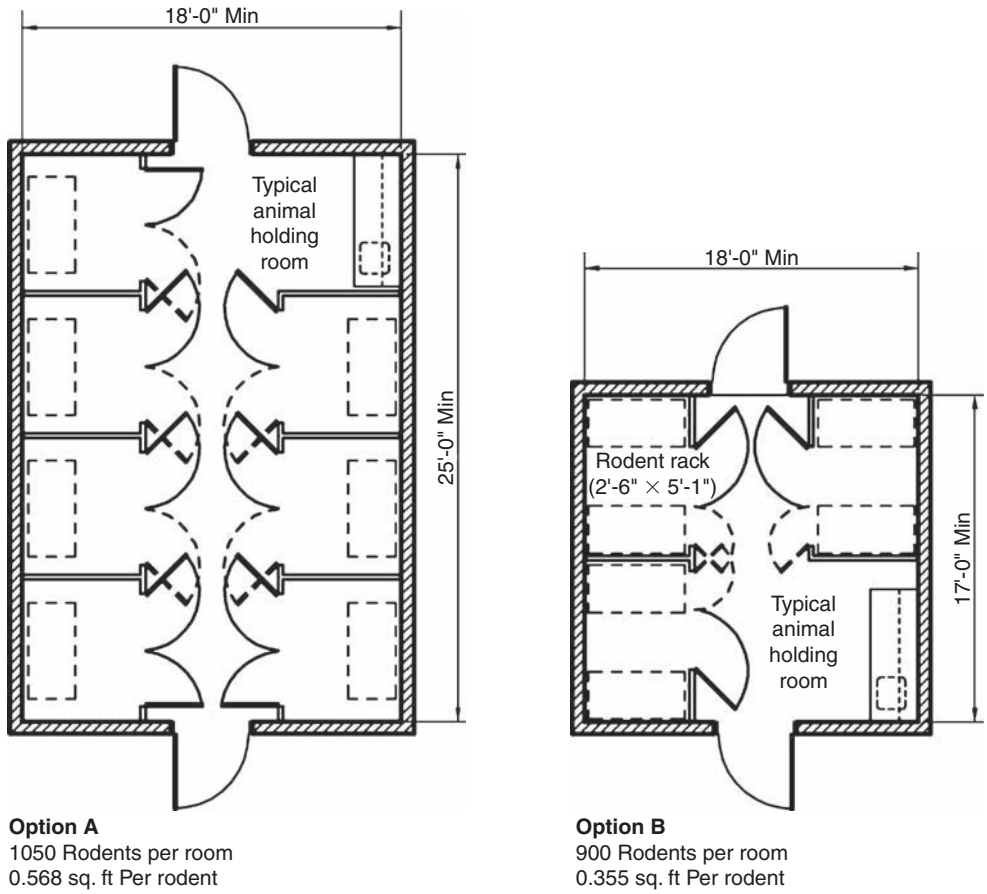
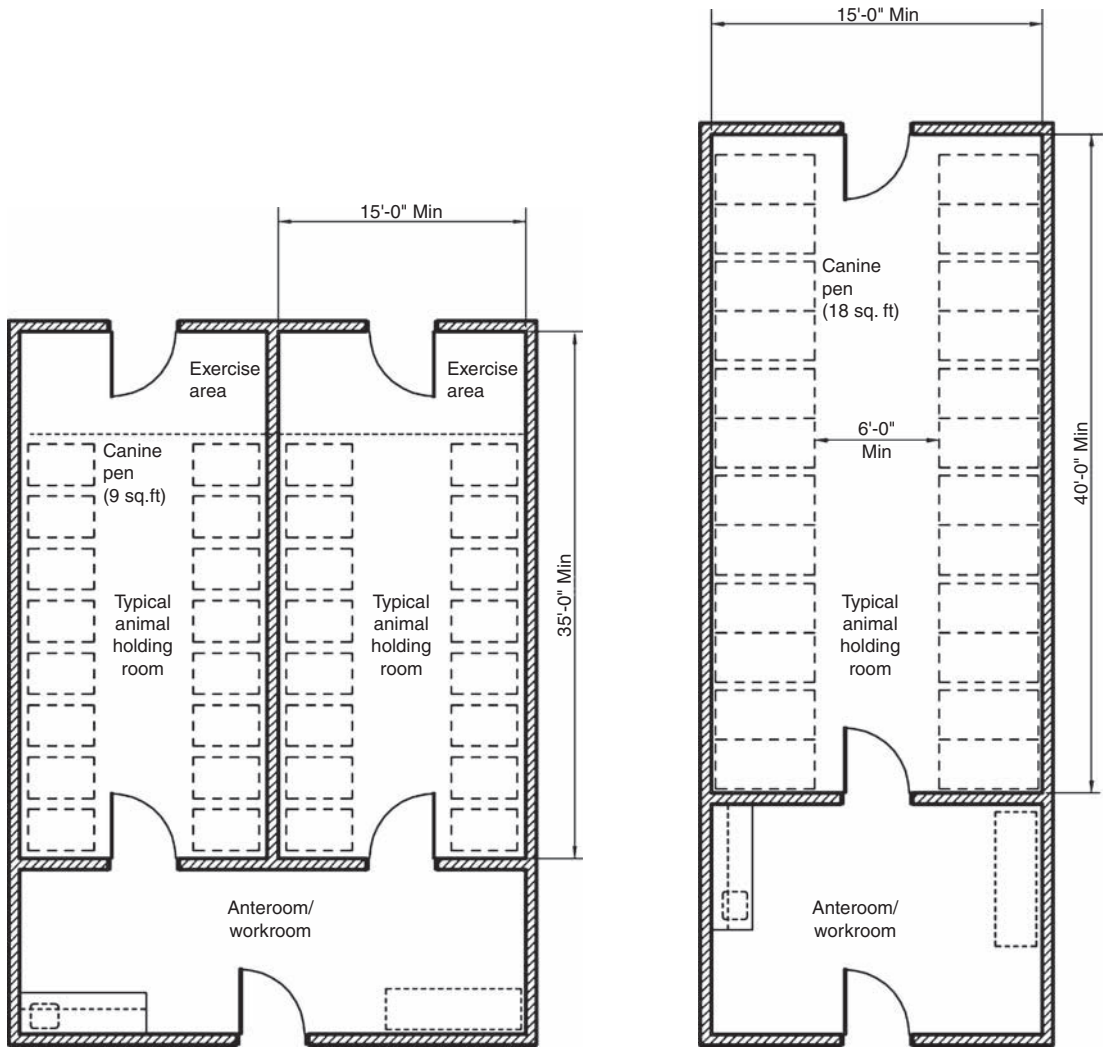


Fig. 4-9 Rodent cubicle room diagrams.

(such as with rodents in bio-safety cabinets (BSCs)), while at other times procedures may be done in an anteroom. In other cases, procedures may be conducted outside the animal holding area within dedicated procedure rooms; this commonly occurs with specialized animal procedures and larger animal species.

The type and frequency of procedures and whether facilities are shared or dedicated to specific procedures will greatly impact the space requirements and the layout of the facility, and therefore need to be well defined on an area-by-area basis. For example, if small animal rooms are clustered adjacent to an anteroom, the size and type of the anteroom will be dependent on the number and frequency of procedures conducted. Another arrangement provides for a "spare" holding room in the suite, which can also be used as a procedure room (Figure 4-11). The use of modular casework provides the opportunity for increased flexibility of interconversion of holding and procedural space. If surgical facilities are needed for larger animal species, the types, frequencies and duration of surgical procedures need to be analyzed to provide the proper ratio of these facilities to the total animal holding capacity. If too many surgical facilities are planned and go unused, it would be a considerable waste of space and investment. However, if not enough surgical facilities are planned, the animal holding capacity will be constrained by the lack of available surgical space. It may be advisable to locate special facilities in such a way that they can be expanded at a future time without undue expense (for example, adjoining animal rooms on at least one side). If they are boxed in on all sides with other expensive specialized spaces, expansion may not be feasible. Many issues regarding the operational aspects of procedure space need to be analyzed at this early design stage – for example, are facilities shared between groups of scientists? Sharing of limited procedural space between different scientists can be a significant constraint on the research productivity. Is the procedural space dedicated to specific scientific specialties, or to core facilities that span across disciplines (Figure 4-12)? Procedure space may be located immediately adjacent to animal holding rooms (Figure 4-13) or distant to the animal rooms. Specific facilities, such as barrier facilities, require additional procedure space for housed animals so that activities may occur without animals leaving the protected environment and potentially influencing animal health. If cubicle facilities are planned they will typically be grouped around a shared procedure area that may serve between 4 and 10 cubicles.

If a facility is dedicated to ventilated racks, the requirements for taking individual cages out of the rack and manipulating the



Option A
32 Canines per room
43.9 sq. ft Per canine

Option B
24 Canines per room
45.1 sq. ft Per canine

Fig. 4-10 Canine suite diagrams.

animals within the room should be considered. Many facilities utilize portable hoods or BSCs for this purpose, which will require utilities as well as potentially additional aisle and parking space in the holding rooms. The placement and sizing of ingress and egress doors are of critical concern with regard to cage flow and frequency of sanitation.

c. Support Space

In addition to procedure space, the design team needs to consider for the following functions (NIH, 2003):

- animal receiving and entry into the facility;
- necropsy and carcass disposal by digestor or incinerator;
- feed and bedding receiving, distribution and disposal;
- dedicated truck dock;
- cage sanitation and sterilizing facilities;
- staff amenities and support facilities;
- provisions for bulk sanitizing agents.

The types and sizes of support areas can vary between facilities and will greatly impact the efficiency of animal care operations.

It is important that these functions be diagrammed to assist the design team in understanding the sizes and functional relationships (Figures 4-14, 4-15). A checklist of functional areas should be consulted to ensure nothing is missed (Figure 4-16).

The design criteria for critical areas, such as the cage-wash (Figure 4-17), should be diagrammed in suitable detail. In

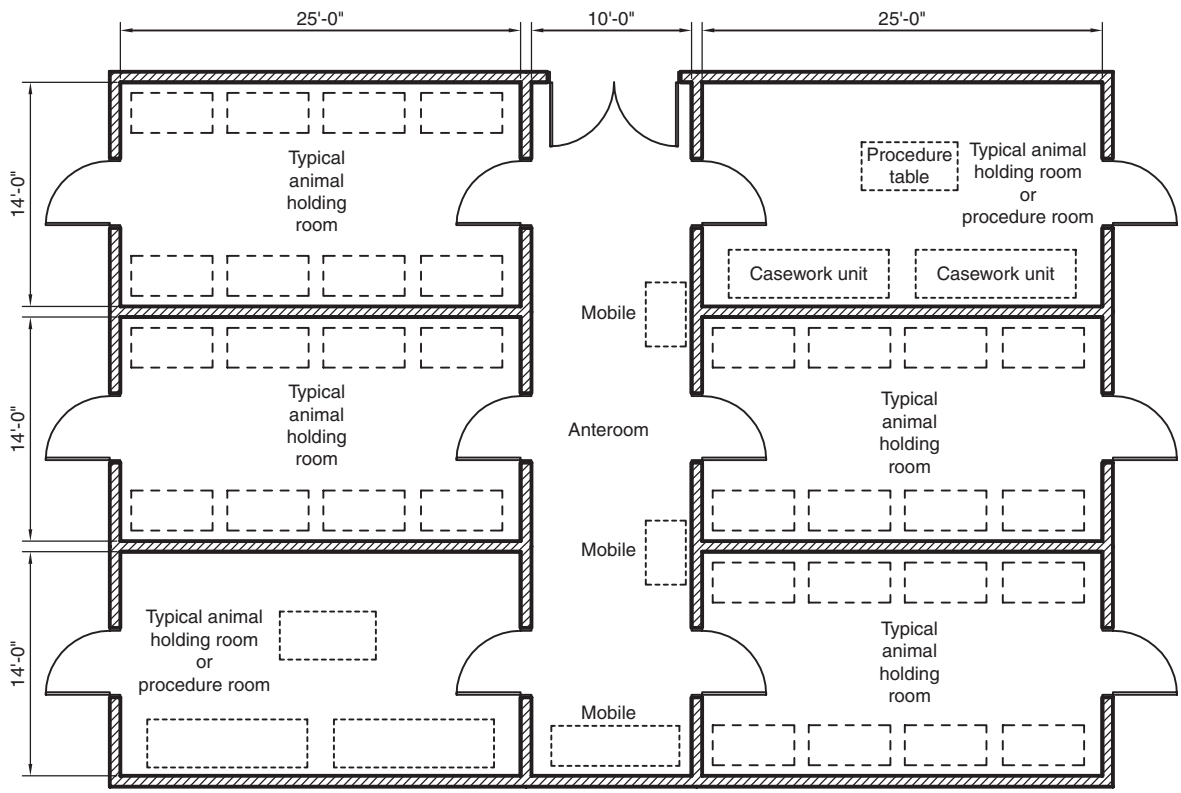


Fig. 4-11 Multi-suite diagram with convertible procedure rooms.

Core facilities should be considered for:

- Imaging
- Diagnostic/phenotyping
- Genetic manipulation (e.g., transgenic)
- Behavioral and neuroscience
- Metabolism
- Irradiation

Fig. 4-12 List of basic core facilities.

Fig. 4-13 Two-room suite with anteroom showing portable sink and equipment bench.

addition, location of staff amenities, such as locker rooms and a break room (Figure 4-18), should be considered during the programming phase.

d. Floor-to-Floor Height

A major subject to be considered by the design team is the floor-to-floor height of the structure or, in the case of a single-storey structure, the floor-to-roof height. Many facilities constructed in the past lacked adequate ceiling space. Today's facilities should be planned for no less than 15′ floor-to-floor height to accommodate the support duct work, piping, electrical and data utilities required for a well-functioning animal facility. The initial cost of adding 1 foot in building height to the design is insignificant compared to the cost of cramming additional duct work, pipes and wires into confined ceiling spaces in the future. In some instances, provision of a fully accessible "interstitial space" (i.e., a walkable mechanical level) between each pair of floors in a multi-storey building should be considered. While this is by far the most flexible solution, it is inevitably the most costly (Figure 4-19).

4. *Net Building Area*

Once the planning team has completed the interview and programming process, the total net building area can be

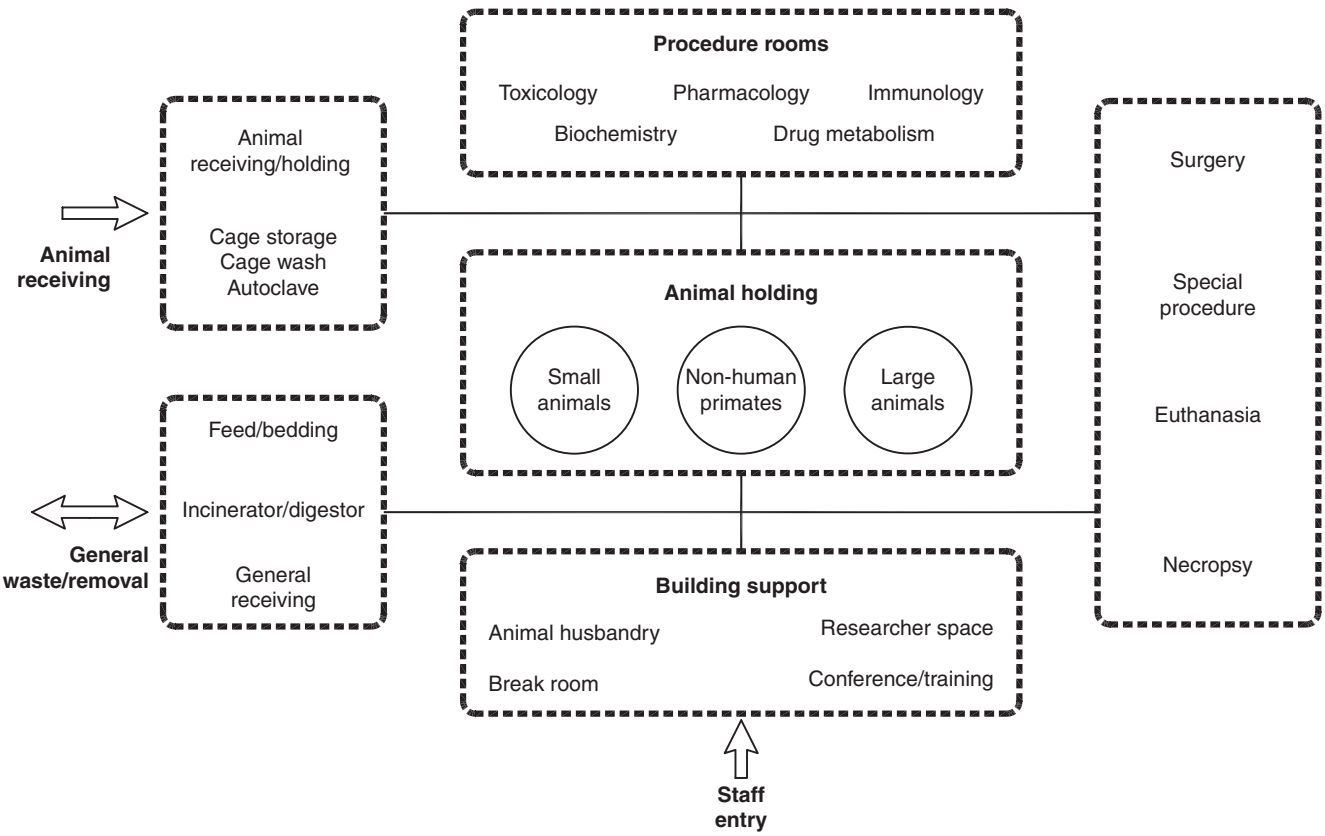


Fig. 4-14 Programmatic diagram of a vivarium.

calculated by totaling all the room requirements and square footages. Space projections should be calculated based on a defined maximum occupancy level for the animal holding rooms within the facility. Although the planned maximum occupancy percentage will vary between facilities, 80–85 percent is commonly used. It is at this stage, when the net building area is summarized, that a first check against the building budget can be made. An example of a net building area tabulation is shown in Figure 4-20.

Even before a building design is committed to paper, tabulation of the net building area against the experience factor of construction and project costs on a net square foot basis will provide a check between the reality of the building program and the available budget dollars.

5. *Gross Building Area*

Once the design team agrees upon the net building program, the gross building area can be tested against floor plans, as well as by comparing it to the "net to gross multiplier" (sometimes referred to as "net to gross ratio"). Typically, the net to gross multiplier for animal facilities ranges from 1.8 to 2.2 × net square feet (nsf) to determine the total gross square feet (gsf) of the facility, which equals a "net to gross ratio" of 45–55 percent. A significant impact on the actual multiplier is the type and location of mechanical systems that support the facility. Other major impacts are the single-corridor vs dual-corridor concept (Hessler, 1991), and whether the building has one or multiple storeys. Single-storey buildings tend to be most efficient because their support functions, such as the cage-wash, are centrally located in one area. In multi-storey buildings these areas will need to be duplicated, and space must be added for elevators, stairs and mechanical shafts.

B. Schematic Design

Schematic design begins after approval of the facility program and conceptual master plan. It is during this phase that the floor plans and elevations are worked out. Basic structure and engineered systems are developed in drawing rooms, and finishes and standard details are agreed upon. This is a transitional phase between programming and definitive design of the facility. The transitional phase consists of exploring the possibilities of alternative design concepts. Schematic diagrams of spatial relationships of functional components will be developed. Multiple iterations of the spatial diagrams are arranged and rearranged, and eventually transformed into

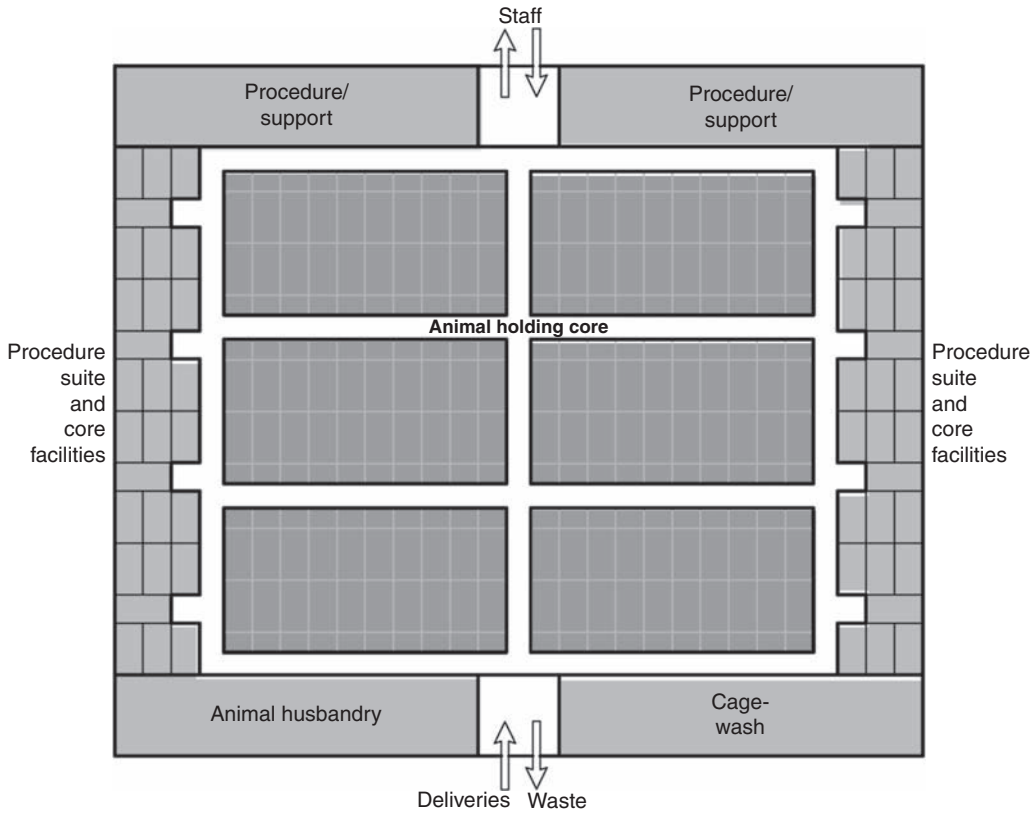


Fig. 4-15 Example of an optimal concept diagram.

design concepts that will be presented to the institution for review and acceptance.

The schematic design effort typically takes 1–3 months at the beginning of each project. An example of a 1-month effort might be a single-storey, 30,000-gsf building that has an overall design and construction schedule of 20 months. Conversely, a 3-month conceptual design effort may be needed for a 200,000-gsf multi-storey facility with a design and construction schedule of up to 36 months.

During this phase, the project team should also consider HVAC and structural engineering designs.

C. Design Development

Important operational decisions need to be made during the design development phase. One major activity is risk assessment (see "Risk assessment," below, for detailed information about evaluation and counter measurements).

The following items, although identified during programming, need to be confirmed:

- the level and frequency of cage or pen sanitation (e.g., in room vs centralized cage-wash);
- the size and location of sanitization equipment and staging areas;
- floor drains vs no floor drains (see "Engineering," below);
- automated watering systems vs individual bottle systems.

New technologies, such as the individual water pouch instead of bottles, are constantly evolving, and must be considered where appropriate. Floor and wall finishes need to be selected early in this process. Examples of different floor finishes are listed in Figure 4-21. Appropriate systems, materials and finishes are described in detail within Part IV of this book.

It is also appropriate at this stage to prepare detailed room-by-room definition or space data sheets for the entire building program. The typical room data sheet, as shown in Figure 4-22, details all room sizes, requirements, finishes and technical details.

These room definition sheets, at this early stage in design, are a work in progress, and are usually issued as an appendix to the program of requirements report. During later stages of design, it is important that these room data sheets be kept updated and are reviewed on a regular basis.

1. *Engineering*

As part of establishing the engineering criteria for the building, it is important that user groups be consulted in the setting of specific design criteria for each of the engineered systems.

Animal colonies zone:
Animal holding rooms
Ante rooms
Procedure rooms
Special procedures room
Quarantine rooms

Animal colony support zone:
Surgical suite(s)
Test reading
Necropsy
Sacrifice rooms
Pathology lab
Tissue histopath
Research tox lab
Study set up room
Special study rooms
Light control chamber
Environmental chamber

Support facilities zone:
Animal receiving dock
Service dock area
Soiled cage-wash area
Clean cage-wash area
Cage storage
Feed storage
Bedding storage
General supplies storage
Instrument supplies
Frozen/refrigerated storage
Housekeeping closets
Decontamination area
Incinerator/digestor

Infrastructure zone:
Chiller plant
Mechanical upper level
Electrical swichgear rm
Emergency generator room
Data network closets
Electrical closets

Staff support zone:
Toilets
Lockers & showers
Scrub & gown areas
AR staff workareas
Breakroom
Training/conf rooms
Visiting scientists area
Observation areas
QA staff areas
Data entry areas

Fig. 4-16 Checklist of functional areas.

The building users need to understand how these criteria will be met by the engineering design.

a. Heating, Ventilation and Air Conditioning (HVAC) Systems

Environmental parameters of animal-holding and -use space are controlled by the HVAC system, which has been recognized to have unique design requirements for animal facilities (ASHRAE, 1999). Defined temperature ranges and acceptable variations, as well as relative humidity and air exchange criteria, must be considered for all species to be housed in the facility (ILAR, 1996; NIH, 2003). Location and types of exhaust systems are important in preventing odor complaints and contamination avoidance. Since most animal facilities will utilize "once-thru air systems," current energy codes mandate that energy recovery systems be considered. The HVAC engineers must provide a clear understanding of how the mechanical systems will operate and adjust to meet varying room conditions. Particularly in rooms that will house rodents in ventilated racks, the design engineers need to consider the cage-level micro-environment in their design. Of equal importance is how the temperature controls will interface with these systems in terms of time delays and monitoring alarm ranges.

b. Drainage

Another aspect of engineering that needs early discussion is the concept for plumbing design, particularly in facilities where floor drains and trench drains are used. Drains are common in facilities for larger animals, but are not typically provided in rodent rooms, unless they are capped for future flexibility. In most instances the drainage systems in single-storey buildings are buried below the floor slab, and thus will be inaccessible in the future if problems arise. The initial layout of these drainage systems is essential to flexibility and avoidance of future operational problems. In many instances, if a room has multiple floor drains or trench drains, they can be served by separate laterals with minimal initial cost. This solution provides redundancy in the drainage systems, and avoidance of room or area flooding in case of a clogged drain line.

c. Electrical, Lighting and Data Systems

Proposed electrical systems should be reviewed for location and intensity of lighting in the holding rooms and lighting controls. The *Guide for the Care and Use of Laboratory Animals* recommends a light level of 30 foot-candles (325 lux) at 1 meter above the floor level (ILAR, 1996). Cages and equipment in rooms greatly diminish light intensity and distribution in rooms. Facilities typically find that light levels of 30 foot-candles need to be augmented during husbandry operations, such as allowing proper observation of the animals and to provide more constant light levels at all cage levels. A greater number of facilities require sophisticated dimming systems to more accurately approximate day/night cycles in the animal holding facilities.

Data ports for data acquisition and recording are an important requirement in the modern animal care facility. Consideration also should be given to present or future plans for radio frequency access.

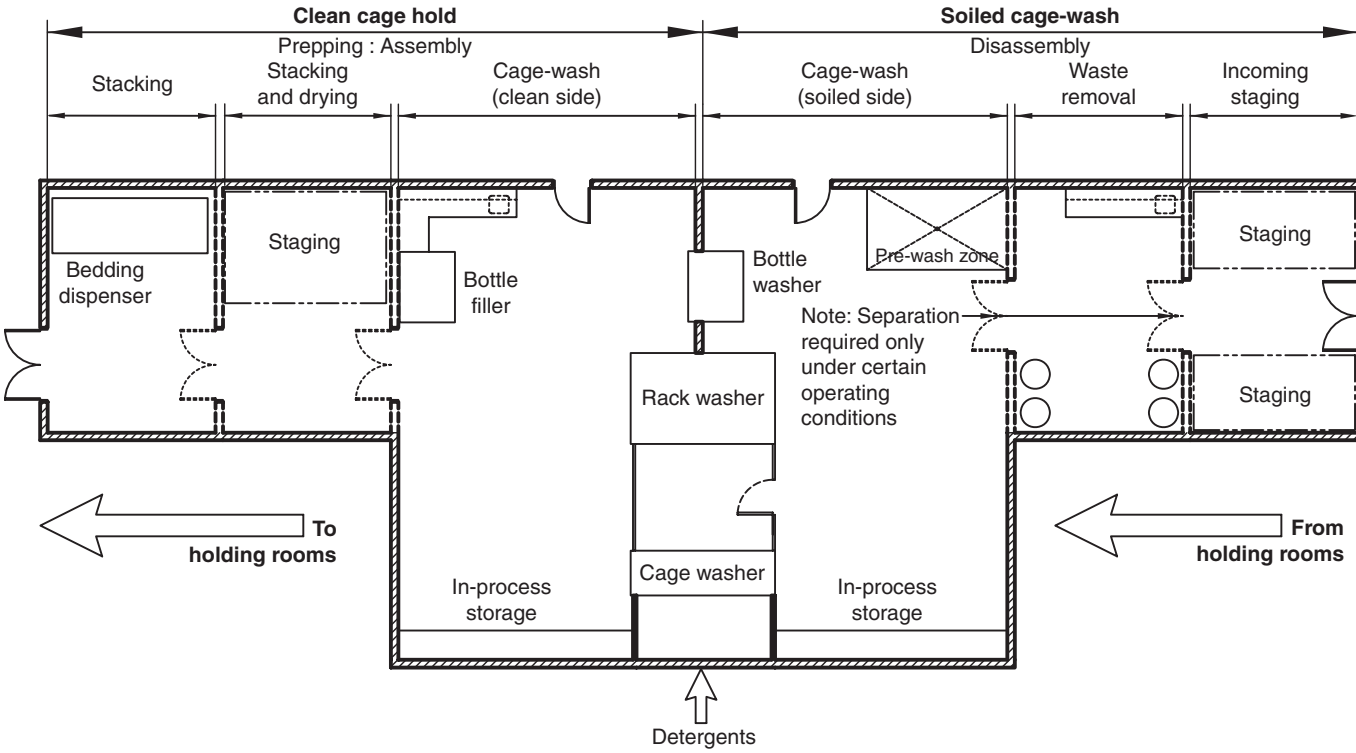


Fig. 4-17 Typical cage-wash area concept diagram.

d. Fundamental Design Report

All engineering assumptions need to be detailed in a fundamental design report (FDR), presented and reviewed by the design team, and signed off by the users prior to proceeding with detailed engineering. After the FDR has been reviewed and signed, further design changes must be kept to a minimum while final construction documents are prepared. There must be a hold on design changes until after construction documents have been completed and the bidding and construction process has started, rather than making ongoing design changes during contract document preparation. Such design changes will be very costly, and disruptive to the design team and the schedule.

2. *Program of Requirements*

Once design development has been completed, it is important that the programming and design decisions be documented in a program of requirements. Review and approval by project management and future users is essential. The program of requirements, at a minimum, should include the following:

- executive summary;
- building program analysis; consisting of existing plan (if available) and proposed square foot areas, net square foot program summary, optimal programmatic diagrams, diagrams of typical animal holding rooms, procedural suites and surgical suites, as well as alternative programmatic solutions considered;
- a summary of the recommended design solution, including site master plan, phasing of construction, a detailed project description, as well as architectural floor plans;
- accurate project cost estimate summarizing capital expenditures and operating expenses, and identifying annual capital expenditures for the entire project duration;
- a design and construction schedule that shows the major design and construction activities and milestones, as well as areas where overlap and float may occur;
- detailed description of proposed engineered systems to include site civil, structural design and mechanical, including HVAC, display data channel (DDC) controls, process piping and plumbing, electrical, and fire protection;
- a project organization chart showing all project team members with their responsibilities and level of involvement during design and construction of the project.

D. Construction Documents Preparation

It is during this phase that the final drawings and specifications are prepared by the design team. Drawings and specifications are usually organized by design discipline: architectural,

Fig. 4-18 Example of a staff break area which takes advantage of natural light.

Fig. 4-19 Interstitial space provides access for adjustment of HVAC equipment.

structural, mechanical, plumbing and electrical. A substantial-sized project will involve hundreds of drawings and up to a thousand pages of specifications. It is important during the construction documents (CD) phase to minimize design changes to avoid coordination issues. It is most advisable to save design changes until after completion of the CD.

Once the CD has been completed, the design team and owner representatives can discuss the use of models and mock-ups before construction begins (see "Modeling," below, for more information).

E. Bidding and Construction Contract Award

In this phase, the AE team has completed much of their work and the bulk of the project is turned over to the construction team. The construction documents are completed and ready to be issued for bidding.

1. *Construction Approaches*

There are several ways to approach the construction process. The appropriate method varies by project, budget and client.

a. Design/Bid/Build Approach

Design/bid/build is the original approach to constructing a new facility. In this approach, construction documents are issued to an invited group of bidders and, upon receipt of their bids, a general contractor is selected to undertake the construction based on their lump-sum bid for the project.

b. Construction Management Approach

A more recently popular approach, construction management, involves the selection of a construction company based on a percentage fee for handling the project. The construction company then proceeds to select subcontractor bids and handle the construction from this point forward by adding the percentage fee to the cost of the subcontractor's bids. This method is popular because it is perceived to expedite the construction process at a minimal increase in cost, particularly in years of inflation. However, in recent years construction management has resulted in the opposite experience for many clients. A lack of quality control, poor coordination, and cost overruns has led many clients to return to design/bid/build.

There are many variations to these two basic construction procurement methods. Some involve issuing separate bid packages for portions of the project or having a construction management firm provide preconstruction services leading up to a lump-sum bid for the general construction. Each of these methods has its own advantages and disadvantages in terms of cost and schedule. The more sophisticated ways of managing construction projects often should only be used if the client

	Current SF	Proposed	Proposed SF	Remarks
Core functions				
– Holding rooms	5975	3 suites @ 1800	5400	112 max cap/suite
– Anterooms		1 per suite @ 10 × 20	incl	
– Incoming quarantine		1 suite @ 1800	1800	2 rms @ 6 racks
– Receiving/shipping dock		20 × 70	1400	incl sanitation station
		subtotal	**8600**	
AR support functions				
– Treatment room/laboratory	600		700	
– Feed storage	226		300	200 sf refrigerated storage
– Supplies storage			200	
– Cage-wash	1257		1500	2 rackwashers @ 1 rack size
– Waste handling dock/containers			200	
– Transport cage/equipment storage/repair	470		500	
		subtotal	**3400**	
Staff support functions				
– Entrance vestibule			100	
–Toilets/lockers/showers			500	1@200, 1@300
– 2 Offices	859		220	1@120, 1@100
– 5 workstations			325	
– Conference room/training/breakroom			400	
– Records storage			100	
– Office supplies storage			100	
		subtotal	**1745**	
Building support functions				
– Mechanical room & penthouse			15000	12800 sf mech penthouse
– Electrical/data/communications			1000	
– Housekeeping closets			160	
– Main corridor	3327		2445	
		subtotal	**18605**	
	12714	total	**32350**	

Fig. 4-20 Example of net building area tabulation.

	Small-animal rooms	Large-animal rooms	Corridors	Procedure rooms	Cagewash	Installed Cost range $$/SF
Trowelled epoxy	**1**	**1**	**1**	**1**	**1**	6.50 to 10.00
Methylmethacrylate	**1**	**1**	**2**	**1**	**2**	7.50 to 12.50
Seamless vinyl	**3**	**5**	**4**	**2**	**5**	5.00 to 9.00
Vinyl ester	**1**	**2**	**3**	**2**	**3**	5.00 to 11.00
Broadcast epoxy	**5**	**4**	**4**	**4**	**3**	3.00 to 5.50
Thin coat urethane	**4**	**5**	**5**	**4**	**5**	1.00 to 2.50
Quarry tile	**5**	**5**	**5**	**5**	**3**	8.00 to 12.50
Performance :						
1 = Best						
2 = Better						
3 = Good						
4 = Minimally acceptable						
5 = Not recommended						

Fig. 4-21 Comparison of typically compared floor finishes.

Project Statement of Requirements
Appendix – Room Definition Sheets

Project Title: Quarantine Facility

Revision No. 6 **Issued:** December, 2004 **Page 1**

Department:	NHP	**Room Number:**	201,204,205,208,209,212
Room Name:	NHP SUITE ROOM A/C		Support Rooms 203,207,211
Room Function:	NHP HOUSING IN 7 RACKS @ 8 PRIMATES = 56 MAX CAP		

Architectural Features

Net Area:	600 sf each A,C/300 sf each support room	Ceiling Height:	9'-0"
Hours of Operation:	24/7	Door Size (Minimum):	4'-0"x7'-0" PAIR
Occupant Number:	56 PRIMATES + 2 STAFF	Door Hardware (Special):	Vision Panel (operable)
Room Finishes		Wall/Corner Protection:	yes
Floor:	Troweled Composite Sys.	Other:	extend floor epoxy up side walls behind cageracks
Base:	Integral Epoxy Cove Base		
Walls:	CMU/Epoxy Paint		
Ceiling:	FRP		

Casework		**Universal Precautions**	
Countertop:		Fume Hoods:	
Wall Cabinet:		Bio Hoods:	
Base Cabinet:		Eye Wash:	No
Knee Space:		Emergency Shower:	No
Other:		Other	

Plumbing Utilities (Quantity/Type/Features)		**Gas Utilities**	
Domestic Water Supply:	Hot & Cold	Oxygen (O_2):	No
Sanitary:	Bio-Waste	Vacuum (V):	No
Lab Waste:	No	Nitrogen (N_2):	No
D.I. Water:	No	Compressed Air (CA):	No
Animal Watering:	2 sides for 7 racks Other: No		
Floor/Trench Drain:	2 sides w/dual drains		
Hose Bibb:	Hot & Cold – Hose Station		

HVAC (Heating/Ventilation/Air Conditioning)			
Design Temperature:	74 ± 2F (64−84F)	Primary Filtration:	30/95% eff. supply
Relative Humidity:	50% +/− 10%rh (30–70% rh)	Exhaust Filtration:	25% eff.
Pressure Relationship:	Negative	Exhaust Location:	Hi/low wall
Total Air Changes/Hour:	15–18 ACH exhaust	Other:	

Electrical Power (Quantity/Type)		**Lighting**	
Duplex Receptacle:	X2 WP	General Fluorescent:	1 × 4 fluorescent – gasketed
Plugmold:		Undercabinet:	
Special Receptacle:		Other:	Edstrom 5 lighting control system (2 stage)
Isolated Circuit:			
Emergency Power:			

Communications: Security		**Communications: Miscellaneous**	
Door Hardware:	card reader on corridor	Paging:	
Video Cameras:	doors	Other:	
Alarms:	Strobe FA		
Other:			

Fig. 4-22 Example of a room definition sheet.

organization has sufficient in-house project management and engineering expertise to oversee the construction process itself.

Specific project requirements spelled out in the facility program document are often augmented by facility standards and corporate engineering standards that apply to the building project. It is important for the project team to stay focused on the overall goals of the project. Usually this means facilitating a smooth design and construction process, leading to a facility

Project Statement of Requirements
Appendix – Room Definition Sheets

Project Title: Quarantine Facility

Revision No. 6 **Issued:** December, 2004 **Page 2**

Department:	NHP	**Room Number:**	201,204,205,208,209,212
Room Name:	NHP SUITE ROOM A/C		Support Rooms 203,207,211
Room Function:	NHP HOUSING IN 7 RACKS @ 8 PRIMATES = 56 MAX CAP		

Communications: Data		**Communications: Monitoring**	
Telephone:		Central:	
Date:	X2 WP	Other:	
Other:	Flat screen enclosed video monitor		

Fire Protection			
Wet Sprinkler:		Other:	Pre-action sprinklers
Dry Sprinkler:			
Chemical:			

ROOM EQUIPMENT SCHEDULE

EX = Existing; N = New; FB = Furnished By; RB = Relocated By; RIB = Rough-In By; IB = Installed By; CB = Connected By

No.		EX	N	FB	RB	RIB	IB	CB
1	TV in waterproof box		X					
2	Hose Station		X					
3	(7) 2 over 2 cages		X					
4								
5								
6								
7								
8								
9								
10								

Miscellaneous Notes:

Sound Proofing needed in all walls in this area; NC criteria TBD.
Basis of Design NHP rack: Carter Systems 76"W × 30"D × 82"H
Rack w/6.3 sft cages (reference 4/16/04 correspondence)

Revision History	
No.	Date
1	8/12/04
2	12/20/04

Fig. 4-22 Continued

that meets the stated design objectives, and is constructed on time and within budget.

2. *Equipment Purchasing*

A subject that needs to be addressed prior to the start of construction is the handling of equipment purchases for the facility. Animal-care facilities have a substantial investment in cage-washers, autoclaves, automatic watering systems, and caging that many clients prefer to purchase directly, as opposed to having the general contractor purchase these items for them. By buying the items directly, a financial "mark-up" on the equipment by a general contractor may be avoided. However, coordination issues between the construction and

the equipment purchase may arise. If equipment is purchased without careful coordination with the construction activities, it can result in significant additional cost due to unloading, placement, installation and clean-up during construction, as well as technical coordination with utility connections. Typically, the vendor of the equipment will not accept responsibility for these items.

F. Construction Phase

While the visible milestones of the construction process are the groundbreaking "topping out ceremony" (i.e., when the last structural beam is placed) and "ribbon cutting" at the completion of a project, there are many more events that lead up to the visible ones. It is common for an overall project schedule to identify a milestone at the end of each design phase, when formal design presentations and reviews are conducted and the client representatives are given the opportunity to comment on the design and engineering plans prior to the start of construction. Similarly, during construction there need to be milestone inspections where the user representatives can review progress on site and assess the status of construction before commissioning and validation activities begin.

1. *Schedule*

One of the most important aspects of any project team's responsibilities is establishing and carefully monitoring the overall project schedule. Typically, the schedule is co-developed by the project managers during initial start-up phases. It is important that the schedule be reviewed carefully and understood by the project team members, and that they agree with the overall schedule and method of monitoring and adjusting it over time. Many software programs can be very helpful tools in giving all members of the design team regular updates on the project status relative to the overall schedule. Regular project meetings need to address, briefly and succinctly, the current status of design, engineering or construction as it relates to the overall schedule. Any changes in the schedule should be discussed at project meetings in order to keep all parties informed.

In many instances there will be pressure on the design team to shorten the schedule by avoiding certain steps. Many projects proceed on a "fast-track basis" and go directly from master planning into detailed engineering and then into construction, thereby avoiding the design development and bidding steps. If the construction management approach is used, sometimes the bidding and contract award period is skipped. While many things can be done to expedite a construction schedule, the design team should consider these activities carefully. Saving time often means spending extra dollars due to redesign and field changes.

2. *Occupancy Planning*

Early in the construction phase, the client's project manager and user representatives should initiate occupancy planning for the building. At this stage the planning focuses on the client's internal occupancy issues, and the design, engineering and construction firms have limited involvement.

G. Commissioning

Most new animal-care facilities constructed in the past 20 years have achieved some level of commissioning prior to operation. The commissioning process can be as simple as the architects and engineers making inspections and preparing "punch lists" for follow-up by the construction contractors, or as complicated as the total validation processes. It is important that the level of commissioning be determined during the construction phase by developing and documenting a well thought-out commissioning plan outlining the process and level of documentation required for successful commissioning (Hessler and Leary, 2002). An example of a commissioning flowchart is shown in Figure 4-23.

A separate commissioning agent is often employed by the owner to verify that contractual agreements have been met. Commissioning is a quality control process to facilitate and verify that the facility and all its systems will perform as intended, meeting the owner's expectations and the functional and operational requirements specified in the facility design. It is not simply the start-up of systems at the end of a construction project. The goal should be to end up with a fully functional facility, with complete documentation and an adequately trained operational and maintenance staff. To be effective, the commissioning process should start at the programming phase and continue through the period of contractor warranty.

H. Validation

In recent years, many vivarium projects undertaken by pharmaceutical and biotech companies have completed full validation as the work conducted in these facilities, in many instances, must meet Good Laboratory Practice (GLP) regulations and other specific product requirements. Therefore, a validation process should be implemented based on established protocols and standard operation procedures (SOPs) for the facility. In addition, the installation qualifications (IQ), operational qualifications (OQ) and process qualifications (PQ) for each system, space and operation within the animal facility must be verified. Validation is usually accomplished by a dedicated, internal team of specialists, or by retaining third-party validation consultants. A complete commissioning and validation protocol for an animal facility can add as much as 6 months to the schedule, after completion of the construction to achieve operational readiness.

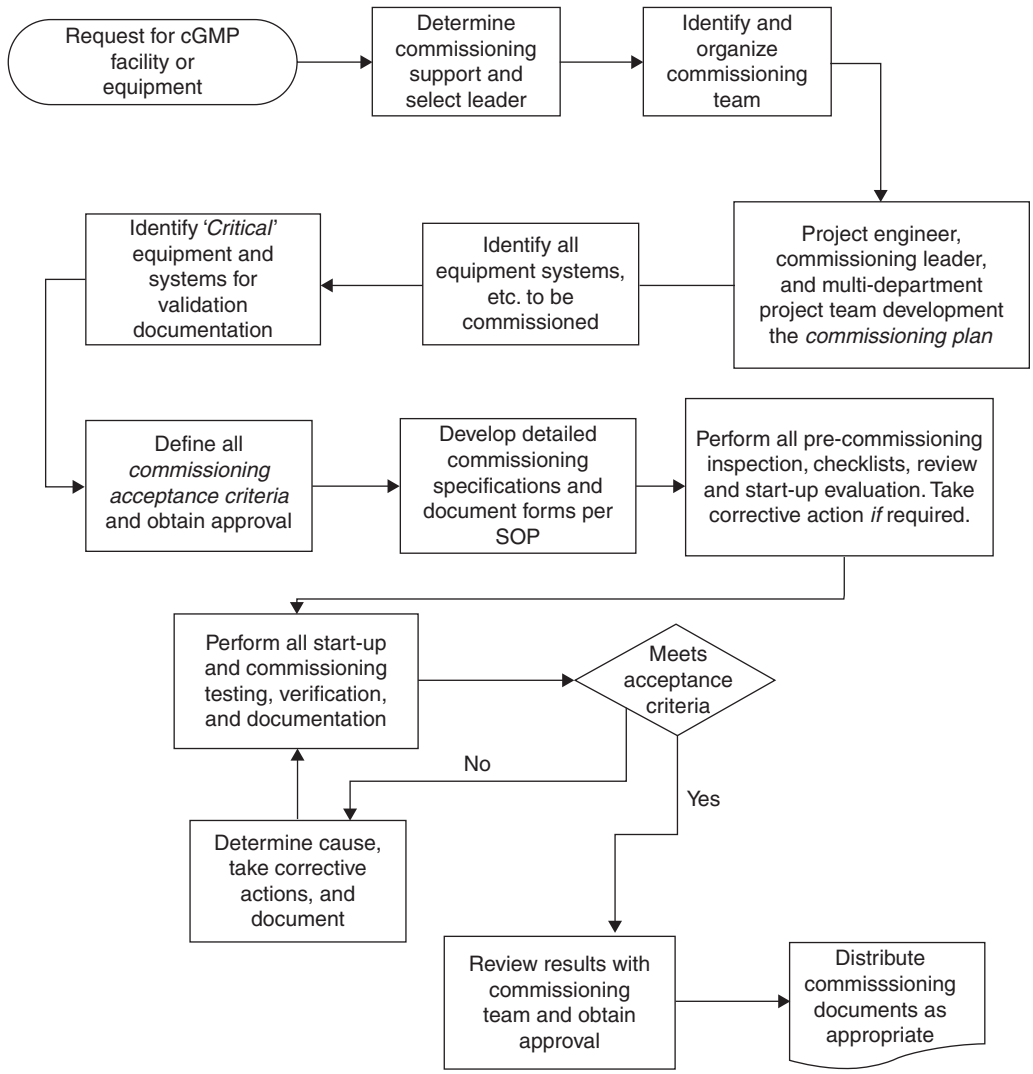


Fig. 4-23 Flowchart showing activities in the commissioning process.

II. RISK ASSESSMENT

In the construction or renovation of a facility designed for animal housing and experimentation, a risk assessment should be conducted to evaluate potential hazards to the facility, whether to the physical security of the building or to daily operations (Copps, 2005; Frasier and Talka, 2005). These known or postulated hazards, also called vulnerabilities, must be evaluated in terms of resultant physical plant damage and impact to facility operations, as well as of establishing the degree of acceptability if they occur. Countermeasures, typically both in construction and operations, are required to minimize the risks associated with the respective hazard. Prevention of every hazard is probably cost-prohibitive in the design of all but a few animal facilities. However, consideration must be given to minimizing hazards to the degree possible while ensuring that the design of each facility meets the needs of its research program. Today's risk assessments for new construction of animal facilities are confronted with many considerations. Growing bioterrorism and animal-rights threats warrant increased security in these facilities.

A. Facility Location Hazards

Many factors influence the final geographic location and design arrangement of an animal facility. Animal facilities within urban areas may be located in below- or above-ground locations, or as part of another research building, to minimize recognition to the public, increase convenience for investigators, and minimize the building footprint. Alternatively,

Natural Hazards	Human-Associated Hazards
Hurricane	Animal Rights Activity
Tornado	Public relations
Flood	Explosion
Earthquake	Employee quality
Winter Weather	Equipment and physical plant malfunction
Temperature Extremes	Terrorism
Fire	

Fig. 4-24 Risks of natural and human-associated hazards.

single-storey animal facilities on the ground floor may be located away from vehicle-access routes and landscaped to deter recognition as a research facility. In either scenario, concealing of the type of research being conducted involves the blending of animal research facilities within the design of adjacent buildings and the topography. Additionally, aligning the animal facility with other research buildings will diminish recognition as an animal facility while facilitating proximity to research laboratories. Convenience to multiple investigator laboratories may drive the construction of many smaller facilities in a decentralized arrangement, while optimal operational efficiency dictates a centralized construction scheme.

Regardless of the final location and design of the animal facility, key considerations must include the unique natural and human-associated hazards that exist in choosing the building site. Examples of such hazards are listed in Figure 4-24.

The potential for natural hazards, commonly described as environmental variables, is readily identified by evaluating historical events in the facility's specific geographical location (Vogelweid *et al*., 2003). Locations in proximity to the ocean must be aware of potential gale-force winds and flooding associated with hurricanes, which may lead to power outages and disruption of daily events. Recent history has underscored the importance of not placing an animal facility in a subterranean location in flood-prone areas without adequate design countermeasures. Animal facilities located in areas prone to environmental extremes, whether located in areas susceptible to extreme winter or to arid weather, must recognize the importance of utility reserve capacity due to power outages.

B. BSL-3 and BSL-4 Facilities

The funding for new BSL-3 and BSL-4 facilities across the nation requires increased risk assessment. With the construction of these facilities, which are commonly located within metropolitan areas, emotional tensions may be elevated due to the nature of the research. Proactive public relations with local civic and community groups ease concerns about the security and biohazard risks associated with the facility location, construction and operation. Due to the passage of antiterrorism legislation, a threat and risk assessment is now required for animal facilities where the possession, use and/or transfer of select agents will occur (Hicks, 2003). This analysis is performed to assess the security and operational effectiveness of the proposed facility design, whereby the vulnerability to threat is compared in a matrix against the impact of loss. A conclusion of the level of risk from each threat can then be incorporated into the physical security design and construction criteria and standards for the associated animal research facility (NIH, 2003; Copps, 2005; Frasier and Talka, 2005).

C. Human-Associated Hazards

Human-associated hazards are mitigated by adhering to local building code requirements, which are written to protect against loss of life and structural damage. A crucial step in the design of a new facility is ensuring that the requirements of the research program are met while conforming to local building codes that may vary by geographical location. If the animal facility is located within a metropolitan area, rapid response times from emergency personnel may be possible; conversely, response times may be prolonged for facilities located in rural areas.

D. Risk Mitigation

1. *Disaster Planning*

The current approach to disaster planning for animal facilities focuses on the development of response plans that become effective once the disaster has occurred and the building has been compromised. These response plans are customized for each animal facility, and commonly are not developed until well after design, construction and occupancy has occurred. However, consideration of the vulnerabilities of the building during its design stage, as well as its location, will assist in an optimal disaster plan. In many cases, revisions in the facility design will provide features to preclude devastating effects on operations.

2. *Recovery Plan*

As part of the disaster plan, steps should be outlined to address correction of any building system malfunction or continuity. Identification and contact information regarding responsible individuals should be defined within the plan.

3. *Security*

As previously described, security of an animal facility begins with its physical location and with limited access to non-essential personnel. Locating the facility within a matrix of other institutional structures and limiting vehicular access are ways to increase perimeter security. A zonal risk approach to facility location may dictate the building site, where a building located within an interior zone is deemed to require greater security measures than one located within an outer zone. For

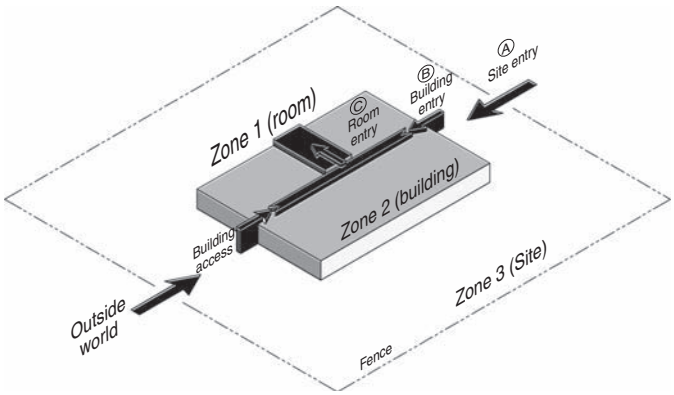


Fig. 4-25 Security zones with control points between each zone.

example, research agents that have a potential use in bioterrorism and may be transmitted by aerosol route should be located within a zone that is physically protected by reduced personnel- and vehicular-traffic patterns. Similarly, a zonal risk approach can be applied within a facility, as presented in Figure 4-25. Physical barriers, such as berms, bollards and fences, as well as electronic surveillance of the facility's exterior, are all design elements that enhance perimeter security. Further, placement of stand-by systems, like emergency power generators, should be within protected areas.

Perhaps the greatest human-associated risk in today's environment requires measures to protect animal facilities from security breaches ranging from simple entry into facilities to sabotage or theft of proprietary property such as research data (Banks, 2003; Richmond and Nesby-O'Dell, 2003; Somin and Wilson-Sanders, 2004b). Although employees may initiate security breaches, the security features of new facility designs focus on preventing access to the entire animal facility or to defined areas.

Facility access measures may vary by facility size. While smaller facilities may use simple key locks, it is most desirable to have an electronic system that maintains a log of people entering and moving throughout the facility at specific times. The majority of electronic systems use either magnetic cards programmed with corresponding identification information or an alphanumeric keypad. However, newer access-control systems for animal facilities may employ biometrics, such as finger- and hand-prints, retinal scans and voice recognition. In many cases, special designs are required to avoid conflict with the existing codes.

Another key security variable for animal facilities involves ingress and egress points, which dictates that a supervised, single-entry point is optimal for control of personnel within the building. As fire codes dictate multiple exit points in case of emergency, doors other than the ingress point must be "exit only" and should be monitored through a security station. In case of an emergency, these exit doors should freely open to allow egress from the facility. Electronic surveillance, at least of access doors or other key areas, should be considered to enhance security. These systems vary from continuous surveillance requiring monitoring by personnel on a 24-hour basis to passive systems with motion-activated recording or notification of security personnel.

4. *Stand-By Systems and Systems Redundancy*

The electricity supplying the animal facility is crucial, as it provides the power for the mechanical systems. Standby power supplied by a back-up generator ensures the health of the animals housed in the vivarium. The back-up generator for the animal facility should be sized accordingly to handle vital systems, such as HVAC, lighting, animal watering, security, and environmental monitoring.

Many systems within the animal facility require built-in redundancy. The HVAC units should have extra capacity to meet demand if a fan or other component is not working. A common HVAC scheme is N + 1 where there is an extra air-handling unit for emergencies. Security systems should have multiple components, as described above, to ensure that if one component is non-functional an alternative component will provide back-up.

III. MODELING

Modeling is advantageous because it provides direction in the choice of various design and construction options for all parties associated with the animal facility project. Institutional personnel or end-users working directly with the architect and contractor can evaluate variations in materials, textures, room configurations and equipment choices. Unanticipated issues in design or materials, or even in the assembly of components, can be identified early and modified to prevent costly changes later on in the building stage of the project.

A. Needs Justification

It is critical to determine the necessity and extensiveness of modeling. This may range from simple variations of a CAD diagram to elaborate construction of an entire room or group of rooms. For example, construction of a large facility with sophisticated or novel configuration of the HVAC system may dictate computational fluid dynamic analysis of airflow patterns and construction of a room mock-up. A small facility with one species may not require such an extensive assessment. Similarly, floor finishes and textures may be evaluated in a room mock-up to confirm the desired product for the installation and provide an example to the contractor (Cuddahy, 2004).

B. Benefits

The benefits of modeling are varied but, at a minimum, modeling allows the project group to function as a team, relying on the expertise of each member in making critical decisions before the construction phase begins. Clearly, any design or material change prior to the construction phase will ultimately save time and money. Thus, any type of modeling should be completed as early as possible in the design and programming phases of the project.

More complex modeling, such as the use of mock-ups, will allow evaluation of actual building materials, test designs and display options. As novel building materials and designs are introduced for use within animal facilities, first hand experience cannot be overstated. This experience will ultimately allow the contractor to establish a mutual standard of quality with the institution. Furthermore, the mock-up provides an example of the expected standard of quality to the various subcontractors on the project.

Finally, the contractor may, during construction of the mock-up, determine that the intended design or materials do not provide the desired results, thus leading to the selection of alternative processes and products. Savings from rework and overall project timelines will benefit from early detection of undesirable products and techniques.

C. Cost and Timing

If differences in opinions concerning materials, finish and design can be resolved early in the process, then the construction can be completed on time, or early, and within the budget constraints. During the budgeting process, a line item associated with the modeling process should be included. Costs associated with modeling are varied, and relate to the extensiveness of the project. Computer models take 1–2 months to complete and require only a modest cost (approximately $10,000 per room model). Actual room mock-ups can range from the modest cost of installing one room early and out of sequence, to the expensive (greater than $50,000) but complete sample room located off of the construction site. Regardless of the modeling exercise, adequate time must be allowed to complete the mock-up well ahead of actual building construction in order for it to be of benefit.

D. Computer Modeling and Computational Fluid Dynamics

Arguably, the HVAC system is the most costly element of new construction and one of the most difficult to change after initial engineering work has been completed. Computer modeling allows early design decisions that will facilitate final configuration and functional requirements. During the 1970s and 1980s, many new facilities experienced expensive retrofits when the HVAC systems failed to perform as intended. Computer modeling of the holding rooms, particularly relating to air distribution, airflow and frequency of air changes, became a successful tool during the 1990s, and continues today to more accurately predict HVAC performance.

Computational fluid dynamics (CFD) is a modeling technique that provides computer simulation of airflow patterns for any room within a facility and has been used successfully (Hughes and Reynolds, 1994; Reynolds, 1994; Hughes *et al*., 1996; Curry *et al*., 1998; Memarzadeh, 1998). Using the specified room design and CFD analysis, airflow patterns can be visualized as influenced by a multitude of variables, including heat loads contributed by animals, room dimensions, orientation of racks and equipment, and air dynamics (e.g., air supply and exhaust locations, velocity of air supply, grill locations, etc.). The effects of the variables are visualized in different view planes by velocity vectors, which are depicted by arrows denoting intensity and direction of airflow. Furthermore, areas where air pockets form due to diminished airflow can be visualized using a three-dimensional view of the room.

Proper airflow patterns assist in reducing recirculation of air and subsequent aerosol exposure of animals and personnel to potential infectious agents and to allergens from animal dander, respectively. Using CFD analysis, airflow parameters can be optimized during the design phase of an animal facility. Computer modeling of the airflow patterns during this phase allows an early and less expensive alternative to evaluation of a constructed model or of an occupied facility.

Computer modeling through the use of CAD drawings is also used during the design phase to evaluate the sizing and configuration of the proposed facility's footprint. Placement of caging, cabinetry and other room equipment will allow evaluation of traffic flow and the development of optimal orientation.

E. Indoor Mock-Ups

1. *Scope*

Indoor mock-ups may be constructed with more flexibility than outdoor mock-ups in regard to location and timing. Although most mock-ups are considered as models of a complete room, they also may be as simple as outlining a room footprint to allow investigators from the institution with an opportunity to manipulate cabinetry and caging configuration within its boundaries. Consensus and involvement of the end-users early in the planning and design stages typically precludes surprises later in the construction phase. Similarly, sections of floor, wall and ceiling with the texture or color of choice may be evaluated by the end-users, as well as the transitions between construction materials and finishes (Figure 4-26). For example, a floor surface in wet areas such as cage-wash requires consideration of a non-slip texture to minimize personnel injuries.

Fig. 4-26 Animal room door mock-up in progress shows hardware and vision panel details.

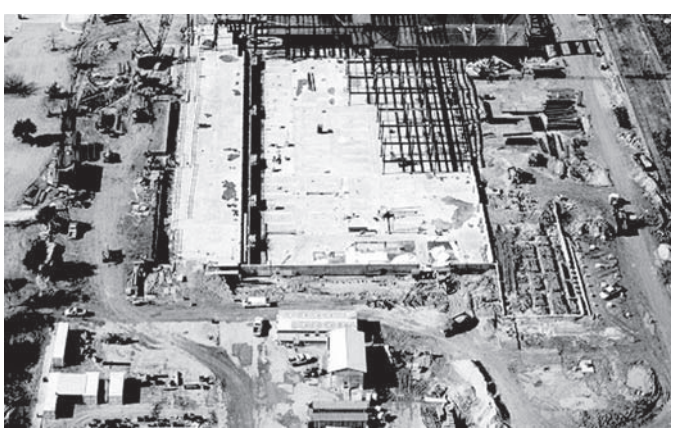


Fig. 4-27 Temporary outdoor room mock-up (lower center) adjacent to new building under construction.

More elaborate indoor mock-ups may be constructed within a warehouse, as a stand-alone structure on the building site (Figure 4-27), or within the shell space of the planned facility. These mock-ups are usually of an entire room or group of rooms, and allow evaluation of more complex issues. They assist the project team and user representatives in evaluating the operation of animal-care and investigative functions within the area, such as ergonomics, functionality and physical relationships of husbandry and investigative equipment, illumination, and acoustics.

2. *Timing*

Early installation is critical, as the usefulness of a mock-up diminishes with time. Review and adjustments will require several months between mock-up installation and final facility installation.

3. *User Reviews*

The end-users should have access to the mock-up for a review process. They should be afforded the opportunity to manipulate sample cage racks for ease of use, to check clearances and turning radii as well as utility locations (e.g., hose bibs, automatic water hook-ups, etc.). Their findings should be documented in a checklist for assessment by the project team (Figure 4-28).

F. Outdoor Mock-Ups

Outdoor mock-ups provide proximity to the building site and allow contractors the opportunity to visualize examples. If the mock-up is located outdoors, exterior finishes and their durability to weather conditions can be visualized under natural conditions. Clearly, exterior mock-ups should be constructed in ample time to allow evaluation under the anticipated weather conditions.

The cost of outdoor mock-ups may be substantial (e.g., $30,000–50,000), particularly if an entire room with all utilities and appurtenances is constructed. If deemed necessary, then this type of mock-up should be the first item on the construction schedule after awarding the project.

G. Lessons Learned from Mock-Ups

Examples of most common changes made after review of mock-ups include:

1. floor and wall finishes – details relating to surface texture and maintainability;
2. drain sizes; locations and floor slopes;
3. fixture types and locations; lights and diffusers;
4. door sizes, swings and hardware;
5. outlet type; number and locations;
6. construction quality; control and supervision required.

Mock-up Checklist

The following items need to be covered:

(1) Exploitation — Does the item meets the expectations?
(2) Quality of product — Is the quality in accordance with the application?
(3) Quality of installation — Has this item been installed properly?
(4) Maintenance — Is this item maintainable?

ref Spec	*Item*	*Facility Engineering*	*Customers*	*A&E*	*Comments*
	Holding room				
03300	Floor (slope, trench)				
04200	Unit masonry				
08100	Metal door + frame				
08700	Hardware				
09545	Ceiling				
09702	Floor finish (resinous)				
09900	Wall finish (block filler & paint)				
10260	Crash rail				
15300	Auto watering (piping-solenoid valve-electrical) (installation)				
15400	Trench drain				
15400	Utility box				
	Moble sink cart connection to UB				
15500	Sprinklers				
15800	HVAC grilles				
15800	HVAC diffusers				
15800	Soffit gordon grid system				
15801	Temp./hum. monitoring panel				
16050	Power outlet (location walls)				
16050	Drop cord reel outlets (ceiling)				
16050	Light switch (location on corr. side)				
16500	Light fixtures (Incl. colored lights)				
16700	Data outlet (location walls)				
	Cages move and fit in room				

Fig. 4-28 Example of a room mock-up checklist.

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Chapter 5

Pre-occupancy Planning, Commission, Qualification and Validation Testing

Michael J. Kuntz and Hilton J. Klein

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I. DEVELOPING A TESTING METHODOLOGY PLAN AND DOCUMENT

"Measure twice and cut once" is a common phrase used in the building trades. This phrase illustrates a common-sense principle that relates to the value of careful and meticulous pre-planning, as well as establishing expected outcomes before the work is actually performed or completed. There is often a point of no return or a very expensive remedy needed to correct mistakes after the actual job has been started or, worse yet, completed. This principle has numerous applications throughout laboratory animal facility construction projects. It must be critically applied to all the physical systems within the new facility, their use once the building is finished, and also

how easily the testing and monitoring of these systems can be performed upon completion. Initially this principle must be applied in the basis of design phase of a facility project, and included in the documents. To ensure a successful final result, significant time and attention to detail needs to be devoted to these documents.

A full understanding of the expected performance criteria for a physical or mechanical system is crucial for all design team members and what the performance limits of the systems will be (Blazewicz, 2005). Most importantly, it is critical that the users of the facility understand how to test the performance of the physical or mechanical systems and document that expectation in a testing/acceptance plan at the basis of design phase, while also establishing the acceptance and rejection criteria and the testing conditions under which those criteria are assessed. Decisions should be made upfront on issues such as who the team members are, how communications will occur and how frequently, and a clear delineation of roles and responsibilities for each team member and agreement reached (Blazewicz and Frasier, 2003). These decisions and the planning will ultimately avoid costly mistakes, facilitate better team dynamics and, most importantly, allow the project to come in on time and on budget (Steiert *et al*., 1995). It is these documents that will be incorporated in the project's testing methodology plan for a given physical plant system, and in all later phases of the facility construction and occupancy project. This plan then becomes an integral part of the building project, and can be utilized to commission/qualify/validate systems during the project's construction phases and as a facet of maintenance in the completed facility (Ruys, 1991; Leary *et al*., 1998).

The test plan will be a part of the design documents, and verified for material components and installation specifications during the construction process. The test plan should be incorporated into the documents, listing critical paths for the project, and clearly capture realistic timelines (allowing time for diagnostic and corrective actions) prior to occupancy.

To illustrate the use of such a testing plan, a chemical delivery and dispensing system in the cage-wash equipment will be utilized. In the example, the chemical system refers to the delivery process of the cage-wash detergent to the desired equipment. It can be a local delivery, within the same room as the equipment, or remote from a bulk storage tank. Detergent product and vendor selection will be simultaneous with facility construction, preceding the testing of the chemical system. The initial user testing will commence after the building is "turned over," and will consist of:

- cycle duration, product concentration per cage type, pH control, and quantity of equipment to be cleaned on a per unit of time basis;
- verification of the desired level of sanitation – visually and microbiologically;
- documentation of each test run, based on pre-established facility SOPs.

Results not meeting established criteria (i.e., failed test) will need to be repeated. It is understood that a similar testing regime with satisfactory results will have been completed by the builder/contractor prior to building turn-over to the users as part of a prequalification period. The main goal of an established test plan is for the team to have discussed and decided in advance on paths forward. Such planning should reduce testing delays and promote resolution of conflicts. Clearly, the testing of the equipment must be done under rigidly controlled conditions, with no undesired variables in the testing scheme. The data collected from validation testing serves as a diagnostic tool for equipment re-calibration, for cause analysis of system failures, and for indicator of quality assurance of design and construction.

Testing may be static, a one-time event. This type of validation or qualification is done when the system to be tested is fully operational, and gives the evaluator a point-in-time assessment of the equipment; however, it does not give a long-term or trend evaluation. In contrast, dynamic testing evaluates a system or process over multiple cycles or through several steps in a cycle. An example of using dynamic testing would involve trend testing (sequential testing over time) of temperature, humidity or particle counts in an animal room over a predetermined time interval. Dynamic testing may last hours or even days (Blazewicz, 2005).

Statistical analysis of data points should be done, especially when troubleshooting systems that appear to be failing to meet the predetermined qualification or validation standards (Steiert *et al*., 1995).

II. HEATING, VENTILATION AND AIR CONDITIONING (HVAC)

The HVAC system includes (Klein and Ubele, 2004):

- mechanical equipment (e.g., chillers, boilers, pumps);
- air handling units (AHU), return fans, exhaust fans;
- reheat coils, humidifiers, supply and exhaust boxes.

The HVAC design criteria must be based on the facility's performance standards derived from *The Guide for the Care and Use of Laboratory Animals* (ILAR, 1996), the species to be housed, and the research function.

Typical operating and testing parameters of the HVAC system (see also Chapter 34) would be:

- temperature set point – the desired condition (e.g., 72°F), usually established in the mechanical control systems (i.e., computer-based building automated control systems);
- control point – actual measured condition at the point of use in a specific location or position in the room or equipment;

- control tolerance – desired minimum and maximum deviation from the set point (e.g., 72 ± 2°F);
- alarm limits – values of conditions which are an excursion beyond the control tolerances that generate an alarm (e.g., 74.1°F).

Similar principles should be used for establishing operating and testing parameters for relative humidity, based on suggestions in the *Guide for the Care and Use of Laboratory Animals* (ILAR, 1996).

Testing criteria of the facility's HVAC system may include the air filtration process. Facilities have either conventional or high-efficiency particulate air (HEPA) filtration systems, or a combination of both. HEPA is defined as 99.97 percent efficiency for the removal of 0.3 μm diameter or larger particles at 85 l/min of airflow. The manner of testing of filtration systems can be further divided into indirect and direct assessments.

A. Direct Assessment

Examples of direct testing in either conventional or HEPA filtration environments include the following.

1. *In-Room Monitoring Equipment*

Calibrated multi-parameter particle ion counters (Particle Measuring Systems, Boulder, CO) incorporate the function of particle counting with temperature and humidity recording. These units can provide 24-hour printed records for test documentation immediately after project turn-over, as well as for periodic maintenance/HVAC troubleshooting following occupancy.

Air change/ventilation rates can be measured directly with handheld anemometers, or with "hoods" that incorporate the anemometer within a cloth-covered frame. The frame fits over the supply or exhaust duct grille to measure the airflow. Typically, room ventilation rates are established as the number of fresh air changes per hour.

2. *Testing in Crisis/Failure Mode*

Because the laboratory animal facility environmental system must respond to severe (crisis) situations during its operational lifetime, these must be simulated prior to use to ensure proper operation at the time the crisis occurs. Each simulation must be supported by documentation. Electrical power can be interrupted to verify that emergency power systems will energize per the design specifications, while temperature and humidity extremes can be simulated to test the heating and cooling capacities and recovery time of the HVAC units and exhaust fans.

B. Indirect Assessment

Indirect testing in either conventional or HEPA filtration environments includes the following.

1. *Computational Fluid Dynamics (CFD)*

CFD is a powerful software analysis tool that utilizes finite-difference techniques to solve highly non-linear differential equations of energy, pressure, relative humidity, air temperature and air velocity. This modeling technique is useful in the design of the project HVAC, including optimum room configurations for given species (Kuntz and Collie, 1994; Hughes *et al*., 1996). CFD can be used to simulate the performance of HVAC systems for ventilation, particulate and odor dispersion, temperature and humidity in a room before actual construction. The current authors have noted that the use of CFD data correlates very well with the actual measured data derived from taking direct measurements of any of the test parameters mentioned above in the completed animal room. This makes CFD a very valuable tool for both predicting optimal design and also pre-occupancy testing validation and qualification. (See also Chapter 35.)

2. *Documentation*

A building monitoring system (BMS) with environmental monitoring capability provides computer linkage from a remote location to the animal holding areas or rooms. Reports from the BMS system provide trending of space temperature, humidity and air exchange rates that are invaluable to verify building design criteria. *One precautionary note:* sensor placement for these systems is usually in the supply or exhaust ductwork and therefore test data results may vary several degrees from in-room monitoring equipment. This underscores the importance of establishing not only how the testing for validation or qualification testing will be performed, but also where the testing will be performed in the room itself (Steiert *et al*., 1995). In facilities without BMS capabilities, testing can be accomplished by manual data collection from animal room and corridor monitors, or by obtaining data from equipment placed directly in the animal room. Artificial heat sources may be placed in a room to roughly approximate the heat supply of a given animal species. In this way, the HVAC system can be tested with simulated occupancy by the laboratory animals. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 1999; http://www.ashrae.org) provides heat-load information from various sources that is very useful in calculating and approximating the heat produced by animal species.

C. Testing Processes Unique to HEPA Filtration Equipment

1. *Biologic Sampling (Direct)*

To determine if the HEPA system is effectively removing bacterial particulates, agar plates can be applied to the animal-room surfaces such as walls and ceiling. Likewise, biological sampling can be utilized on the HEPA filters prior to use to provide a baseline measurement of bacterial growth.

This process will also determine whether the integrity of these filters has been compromised. However, this is a slow and tedious testing method that is expensive and requires special laboratory expertise. It may be used in some situations, but it is not widely employed as a testing method to assure the integrity of filtration systems today.

2. *DOP (Dioctyl phthalate) Challenge to HEPA Filter System*

Adherence to the strict quality standards/specifications of the HEPA filter and its proper installation into the HVAC system are critical for its performance. Fit-testing or verification of installation of each filter must be performed immediately after installation, prior to initial use, and yearly thereafter. To verify the HEPA efficiency, a thermal dioctyl phthalate (DOP) process is used. This process utilizes DOP dust particles, which are mono-sized and 0.3 μm in diameter. They are generated by vaporization and condensation. Following their introduction into the filter, a photometer measures the particle penetration by sensing the scattering of light. Mineral oil may also be used as an alternative to DOP in the testing of HEPA filter performance. Mineral oil is being used with increasing frequency to replace DOP testing (US Department of Energy, 1997).

3. *Laser Particle Counting*

Modern laser particle counters are now commercially available for monitoring of HEPA filtration effectiveness. A variety of counters with varying capabilities and modalities are available (http://www.particlecounters.org). These counters have computerized controls that facilitate testing at specific time-points over extended periods of time, providing trend analysis of HVAC ventilation and filtration systems. Testing over extended time periods provides for evaluation of particulates or even airflow or air migration into a room from corridors or interstitial spaces in the building. This methodology, while expensive to purchase, provides rapid and accurate data on particle counts (an index of filter integrity) without requiring special expertise to operate the equipment or to analyze the data. Alternatively, the equipment may be leased rather than purchased. Many counters also have the capability to monitor both temperature and humidity, using the same piece of equipment. Again, it is critical to establish upfront in the design phase that this or other methodology will be used to establish acceptance or rejection of HVAC system performance and, in the case of laser particle counters, it is also important to establish beforehand the time-points (or trends) that will be used and the location of the sampling sites.

III. CAGE-WASHING EQUIPMENT

Typically, this equipment includes rack washers, tunnel (belt) washers and various types of smaller equipment washers. Pre-planning is the key to testing/qualifying this critical area of the laboratory animal facility. A factory acceptance testing (FAT) plan should be created that outlines pre-testing criteria and acceptance – rejection parameters of the cage washer while it is still at the factory or assembly site prior to shipment and installation. This FAT plan may be included in the purchase agreement for the piece of equipment. Overall, FAT can be conducted while the facility is being constructed, thus saving time for the overall occupancy deadlines and reducing timeline pressures on the design and construction team members when the facility is ready to be fully occupied. FAT involves site-visiting the equipment factory during the manufacturing process, as well as upon completion and prior to shipping. On the last visit, the vendor demonstrates to the purchaser that the piece of equipment can meet or exceed the established agreement specifications, as well as any agreed-upon performance testing on the purchaser's specific equipment. These tests will be repeated and expanded after final installation in the facility, but the FAT provides the purchaser with the additional confidence that the equipment is functional and has been manufactured according to the established specifications (Pouch *et al*., 1997; Merck & Co., Inc., 2006).

New cage-wash equipment is the most time-consuming and complex of the systems requiring validation. It is complicated by the various kinds of caging and equipment to be sanitized (Pouch *et al*., 1997). This system's testing is again divided into direct and indirect assessment.

A. Direct Assessment

Direct assessment consists, in part, of visually monitoring the instrumentation, gauges, seals, etc. associated with the equipment to verify that the supply water is the correct temperature, the steam is of the pressure specified and no fluid leaks are noted. Personnel safety testing should be done to verify that all safety provisions, equipment emergency shut-offs, signage, and door releases (on rack washers) are functional. Visual inspection of the sanitized equipment provides the assurance that gross contamination has been removed and the equipment meets the facility's established standards. Temperature indicators (Steris Corporation, Mentor, OH; Dry Pak Industries, Studio City, CA) are useful tools to determine equipment function and verify that required temperatures are being met. The sensors are attached to the cage or material being sanitized, and the maximum temperature reached during the cycle is permanently recorded on the sensor. The location of the sensor should be varied with each test cycle to provide maximum coverage verification.

B. Indirect Assessment

1. *Biological Monitoring*

Biologic monitoring is used to determine whether the equipment is sanitized per established specifications. Two ways

of testing are by swabbing the equipment or by applying a Replicate Organism Detection and Counting (RODAC®) plate to the sanitized surface before and after sanitization (Ednie *et al*., 1998; BD Diagnostic Services, Speaks, MD). Strict records need to be kept to coordinate the location of the test on the equipment and the number of locations on each piece. The location will vary greatly with the size and shape of the equipment, as well the species housed. Bacterial absence, presence and degree of contamination is compared for the before and after samples. Attention should be noted to sample locations that have animal contact and those that do not. Typically, for the equipment surfaces of each cage type and each species as well as the animal room surfaces, the standard should be ≤ five organisms per RODAC test plate. These same results should be repeatable three (Steiert *et al*., 1995) consecutive times over 2 days (Pouch *et al*., 1997; Merck & Co., Inc., 2006).

2. *Physical Testing*

Initial equipment testing should involve many variables: cycle duration, number of cycles, presence or absence of cleaning products, pre-cleaning process, temperature of water, and conveyor belt speed. The optimum operational settings can be determined to effect a high-level of effectiveness and efficiency. Care should be taken to minimize the number of variables that are changed with each test performed. The time of day of the test can also be a variable, as the supply water temperature may fluctuate depending on building demands outside the animal facility.

IV. ELECTRICAL AND LIGHTING SYSTEM

Prior to occupation of a facility, each receptacle and ground fault device, light switch, light fixture, light-control device and piece of electrical equipment must be verified as functional. This will usually be done manually, although the exception is when a BAS (Building Automation System) controls the animal-room lighting. In this case, the BAS reports would serve as documentation with hard-copy reports. Changing the settings of this lighting system within the BAS to various times will verify functionality and compliance to design specifications.

A. Testing the Light Levels (Intensity) Within the Animal Rooms

The light intensity in the animal rooms is measured in lux or foot-candles. Typically, average light readings using a photometer are taken at 1 meter above the floor at a few locations within the room.

Variations in light intensity over time can be due to light source degradation, dirt accumulation on the bulb, variation in ballast quality/performance or lamp color/temperature, and the use of dimming devices.

The eyes of albino laboratory species are particularly susceptible to high light levels, and retinal damage can result. Recommended light levels for albino animals are 130–325 lux (up to 30 foot-candles) (ILAR, 1996). Desired ceiling light intensity and color is determined in the design phase, and can be simulated using computer programs. After construction, additional refinement of lighting intensity can be achieved through ceiling fixture and/or bulb removal, and by placing tinted plastic sleeves over the bulbs. Alternative patterns of ceiling wiring circuits can also provide flexibility in lighting intensity. If special lighting systems (e.g., red lights) are included in the design, accommodation must be made to validate and test those systems. Such validation or qualification may require special equipment (see also Chapter 33).

V. ANIMAL DRINKING WATER AND PLUMBING SYSTEMS

The animal drinking water system is a potential source of contamination for laboratory animals, and therefore should be installed as a stand-alone system from the source – i.e., not as part of the other plumbing in the facility. The typical equipment of this system is a pressure-reducing station that reduces standard building pressure to amounts that can be utilized by small rodents (this usually serves several holding rooms), a solenoid within the holding room that acts as a back-flow restrictor, the water-delivery lines mounted on the holding-room walls (ideally constructed of stainless steel), and the removable water lines that connect to the animal cage(s). This equipment should be purchased from and installed by a reputable vendor who can offer quality service on a continuing basis after installation. A system-flushing option is strongly suggested, especially if rodents are utilizing the water. This option will ensure that the water in the system is moved through the piping and discarded up to several times per day, reducing bacterial growth accumulation. The animal drinking water may require treatment to eliminate coliforms and *Pseudomonas aeruginosa* (Merck & Co., Inc., 2006).

The vendor should perform pre-installation sanitation and bacterial testing of the water lines. This is critical, and should be followed with water sampling (under sterile conditions) for bacterial contamination by the owner. The design of the system should ensure that there are no “dead-legs” – areas where the water can stagnate – that may facilitate bacterial growth and be sources of potential contamination. Water samples should be collected from the middle and the end of the delivery line “loop” for each pressure-reducing station. Testing should be repeated until each sample meets or exceeds the established protocol. This protocol will also determine the frequency of collection after building occupation occurs. Should water

contamination persist, the vendor should take appropriate action to correct the problem.

Likewise, each separate piece of equipment or system utilizing facility water needs to be tested, to verify that it is not contaminated prior to putting it into service – e.g., UV irradiators, diagnostic laboratory equipment and cage-washing equipment, as mentioned above. If RO systems have been installed, initial membrane integrity must be assured and future routine maintenance scheduled.

VI. AUTOCLAVE TESTING

Similar to the other equipment in the animal facility, the autoclaves require validation of acceptable performance. This discussion will focus on large, wall-mounted autoclaves, but can be applied to smaller units as well, such as table-top units. Similar to cage-washing equipment, the autoclave should have a FAT prior to delivery. After installation, the owner will need to perform "load" testing on the unit. Special attention must be given to the materials tested in the load, and also to their location and packing density within the chamber of the autoclave unit. This involves operating the autoclave with materials similar to those that will be routinely autoclaved. Note needs to be taken regarding material configuration (placement) in each test until an optimum configuration is achieved. To verify that the autoclaved materials have been sterilized effectively, either physical or biological testing can be used. Typical results for autoclave testing should be three consecutive qualifying runs over a 2-day period with no growth noted (Merck & Co., Inc., 2006).

A. Physical Testing

Various "runs" will need to be completed while varying cycle time, materials, temperature and pressure. These must be documented and compared with the autoclave's manufacturer specifications. Upon cycle completion, the material will be swab-tested for bacterial contamination. Each phase of the cycle will also need to be verified for proper mechanical functioning. As noted under "Cage-washing equipment," above, personnel safety testing devices must also be verified.

B. Biological Testing

Following the manufacturer's instructions, bacterial indicators (Verify™; Steris Corporation, Mentor, OH) can be placed within the material to be autoclaved prior to starting the cycle. On completion of the cycle, after activation and incubation of the biological indicator, it will be evident by viewing color changes on the indicator vial whether the material was exposed to the proper environment within the autoclave to ensure sterilization.

VII. NOISE TESTING

It has been recognized for many years that noise in an animal facility can have a negative impact on the animals housed (Peterson, 1980; Riley, 1981; ILAR, 1996; Terpeluk *et al*., 2004; Turner *et al*., 2005). Noise can be defined as sound that lacks agreeable quality or is noticeably loud. It may also create problems even though it is imperceptible to human beings, as many animal species can hear sound at much higher and lower frequencies than people can (Motzel *et al*., 1996). Noise can be generated from numerous sources – personnel moving equipment, faulty equipment, or the animals themselves. The anticipated noise levels should be determined during the design phase, and noise reduction built into the animal rooms during construction. Recent studies (Pryor, 2006) have determined that noise with intensity of 70 dB, considered moderate, can have a negative effect on rats. In this early stage of the facility, the "loud" animals to be housed can be segregated, additional insulation placed in the walls and ceiling, etc.

Attempts to obtain noise reduction or abatement after construction are less than desirable, often not providing the required level of reduction and being very expensive to retrofit (Johnson *et al*., 2005). Many of the products available for installation in the animal room are not moisture-proof or sanitizable, as indicated in the *Guide for the Care and Use of Laboratory Animals* (ILAR, 1996).

VIII. DECISION-MAKING AND FOLLOW-UP

Storage and retrieval of data derived from qualification testing and analysis of the performance data are of tremendous value to the successful commissioning and occupancy of an animal facility. Information that indicates that the facility has been satisfactorily qualified or validated gives confidence to the design and construction team that animals can be safely housed in the facility, and that expensive research projects will not be compromised (Steiert *et al*., 1995). It must be recognized that commissioning is a complex, dynamic process that involves effective communication, and careful planning and execution of the plan. Data and information that are derived from qualification and validation testing can also be used to diagnose facility operating system or mechanical system problems during the construction and pre-occupancy phases. This allows team members to address and solve problems and meet performance specifications and operating criteria. The data from the testing allow problems to be solved objectively and in a cost-effective, timely manner. High-quality data from commissioning studies, once documented, may be supplied to regulatory and accrediting agencies to provide assurance that the construction, installation and operation of the various equipment and mechanical systems are such that they function properly. Overall, the commissioning process, when

thoroughly and meticulously planned and executed, will save time and reduce costs for any organization. More importantly, data and information proving that a facility is functioning to performance standards as determined by high-quality commission planning provide strong assurance that animal welfare, scientific and veterinary medical standards will be met after occupancy of the new facility.

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Chapter 6

Regulatory Issues

Harry Rozmiarek

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I. INTRODUCTION

Regulations pertaining to research animal facilities and their operation in the United States are primarily focused on the provision of adequate animal care. To provide adequate animal care it is essential that certain minimal facilities are provided. The facility required depends upon the species of animal, the level of containment required both to keep the animals healthy and to contain the agent being studied, and the security required to house the animals appropriately and to keep out any physical and microbiological threats. Regulatory issues for animal care and use in the United States can be placed into three major categories: (1) those required by law, (2) those listed as policy and frequently required by federal regulatory and granting agencies but that are not legal requirements, and (3) guidelines that are usually best-practice performance standards which may be interpreted differently depending upon the situation and the nature of the animal-care and -use program. Each of these categories has impacts upon the physical plant of the animal facility. While this chapter is intended to address only regulatory issues in the United States, we must be aware and cognizant of regulatory requirements of other countries which may influence international collaboration in both academia and industry.

II. LAWS AND REGULATIONS

The United States established the "28-hour law" in 1873, which governed the treatment of farm animals during shipment. It specified the maximum length of time animals could be transported before receiving food, water and rest. The first

law in the United States which addressed non-farm laboratory animals was established as Public Law 89-544 in August 1966. Commonly known as the Laboratory Animal Welfare Act, it regulated trade in dogs and cats procured for laboratory research, as well as dogs, cats, hamsters, guinea pigs, rabbits and non-human primates held by certain research facilities. The law was to be administered by the Department of Agriculture and applied only to animals being held, and did not include the time the animals were being used in actual research and testing procedures. In 1970, the Act was amended by Public Law 91-579 (Animal Welfare Act Amendment, PL 91-579, 7 USC, 2131-2156, 24 December 1970) and titled "The Animal Welfare Act." This amendment covered animal care throughout the animals' stay in the facility, including time while research was being conducted. A 1976 amendment, Public Law 94-279 (Animal Welfare Act Amendment, PL 94-279, 22 April 1976) brought common carriers such as airlines under the provisions of the Act, and led to the development of standards for containers and conditions of shipment (IATA, 2006). The term *research facility*, as defined under the Animal Welfare Act, means

> any school (except an elementary or secondary school), institution, organization, or person that uses or intends to use live animals in research, tests, or experiments, and that (1) purchases or transports live animals in commerce, or (2) receives funds under a grant, award, loan, or contract from a department, agency, or instrumentality of the United States for the purpose of carrying out research, tests, or experiments.

The current Animal Welfare Act invests the US Department of Agriculture's Animal and Plant Health Inspection Service with the responsibility for issuing and enforcing regulations regarding humane care, handling, treatment, transportation, general husbandry standards, employee training, veterinary care, quarantine and separation of species. The regulations enforcing the Act (Office of the Federal Register, 2002) include dogs, cats, monkeys, guinea pigs, hamsters, rabbits, marine mammals, other domestic animals raised in captivity, and animals normally found in the wild state that are being used for research, testing, experimentation, exhibition purposes, or as pets. They specifically do not include birds, domestic rats, domestic mice, horses, and farm animals intended for use as food or for the use of improving animal production, breeding, and management. The "Farm Bill," containing further amendments to The Animal Welfare Act (Food Security Act of 1985, Subtitle F – Animal Welfare, PL 99-198), was signed into law and became effective 23 December 1986. Changes have been clarified by the USDA and address (a) exercise requirements for dogs, (b) a physical environment adequate to promote the psychological well-being of primates, (c) details about the organization and functioning of institutional animal care and use committees, and (d) increased penalties for violation of the Act. While none of these specifically regulates facilities, they all require certain minimal facilities to meet the performance standards required. In addition to the Federal Animal Welfare Act, all 50 states and the District of Columbia have animal anti-cruelty laws, and some have laws concerning the use of animals in research (National Association for Biomedical Research, 2004), but none specifically address facilities.

A. USDA Regulations

The USDA has established animal welfare regulations which can be found in the Code of Federal Regulations (Office of the Federal Register, 2002). While these address all aspects of humane animal care and use and do not specifically address facilities, many of the regulations imply and even specify certain facility and operating standards which include indoor and outdoor housing facilities, mobile or traveling housing facilities, and primary enclosures. The following statements which pertain to animal facilities are taken from the USDA regulations, and are followed by some comments and recommendations.

> The facility must be constructed of such material and of such strength as appropriate for the animals involved. The indoor and outdoor housing facilities shall be structurally sound and shall be maintained in good repair to protect the animals from injury and to contain the animals.

While the law does not require sound-attenuation, this should be considered when building animal facilities. Use of durable surfaces coated with epoxy paint or its equivalent should be considered in animal rooms, as well as stainless steel or similar caging materials which are resistant to moisture and corrosion.

> Reliable and adequate electric power and potable water shall be available on the premises. Supplies of food and bedding shall be stored in facilities which adequately protect such supplies against deterioration, molding, or contamination by vermin. Refrigeration shall be provided for supplies of perishable food.

Emergency generators which provide electricity in the event of power failure are recommended, especially in areas of high-density, special ventilated caging units, and biocontainment areas. Separate storage rooms for food and bedding and for cleaning supplies should be considered. Refrigerated storage for all animal food is not required, but extreme temperature variations should be avoided.

> Housing facilities must be equipped with disposal facilities and drainage systems that are constructed and operated so that animal waste and water are rapidly eliminated and animals stay dry. Closed drainage systems …. must be equipped with traps which prevent the backflow of gases and the backup of sewage onto the floor. Dead animals, animal parts, and animal waste must not be kept in food storage or food preparation areas, food freezers, food refrigerators, or animal areas. Washing facilities such as washrooms, basins, sinks, or showers must be provided for animal caretakers and must be readily accessible.

Animal-room drains with a diameter of 4 inches and with rim-flush capability are recommended, and main drain lines should

have a diameter of 6 inches. Drains should be flushed at least once a week to prevent their drying out. Appropriate refrigeration should be provided for perishable animal food as required, and should never be intermingled with personal lunches or other human food. Refrigeration should be provided for animal carcasses separately from food or other refrigeration. It is a good idea to provide showers and washing facilities for animal-care personnel, and adequate lockers and clothing storage should be provided as required.

> All primary enclosures … shall conform to the following requirements: (a) Primary enclosures shall be structurally sound and maintained in good repair to protect [the animals] from injury. Such enclosures, including their racks, shelving and other accessories shall be constructed of smooth material substantially impervious to liquids and moisture. (b) Primary enclosures shall be constructed and maintained so that [animals] contained therein have convenient access to clean food and water as required. (c) Primary enclosures having a solid floor shall be provided with clean bedding material. (d) Primary enclosures equipped with mesh or wire floors shall be so constructed as to allow feces to pass through the spaces of the mesh or wire, provided however, that such floors shall be constructed so as to protect the animals' feet and legs from injury. (e) Space requirements for primary enclosures [are specified in the regulation specifically for each of the different species. These should be referred to when constructing or purchasing cages.] Innovative primary enclosures that do not precisely meet the space requirements … but that do provide animals with a sufficient volume of space and the opportunity to express species-typical behavior may be used … when approved by the Institutional Animal Care and Use Committee, and by dealers and exhibitors when approved by the Administrator. (f) [Special requirements for cats:] The minimum floor space required … is exclusive of any food and water pans. The litter pan may be considered part of the floor space if properly cleaned and sanitized. Not more than 12 adult non-conditioned cats may be housed in the same primary enclosure. In all primary enclosures, a receptacle containing sufficient clean litter must be provided to contain excreta and body wastes. Each primary enclosure … must contain a resting surface or surfaces that, in the aggregate, are large enough to hold all the occupants of the primary enclosure at the same time comfortably. The resting surfaces must be elevated, impervious to moisture, and be able to be easily cleaned and sanitized. (g) [Special requirements for dogs:] Not more than 12 adult non-conditioned dogs may be housed in the same primary enclosure. Permanent tethering of dogs is prohibited for use as primary enclosure. Temporary tethering of dogs is prohibited for use as primary enclosure unless approval is obtained from APHIS.

The Animal Welfare Act and USDA Regulations used in its enforcement take precedence over any policies or guidelines, and are required under the law. Any state, local or municipal requirements must also be followed.

B. Policies

Policies are not legal requirements and do not carry the power of law enforcement, but compliance with policy is required by funding agencies and other agencies of the government for an institution to be eligible to participate in programs granting funds or approval of products. The policies which are most relevant in the United States are the Public Health Service Policy (NIH, 2002), and requirements of Good Laboratory Practices (GLPs) (Code of Federal Regulations, 1978; Office of the Federal Register, 1978) required by the Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA). These policies stem largely from the US Government Principles for the Utilization and Care of Vertebrate Animals Used in Testing, Research, and Training (Interagency Research Animal Committee, 1985). These principles have been agreed upon by all agencies of the US Government, and provide the basis for most other laws and regulations for animal care and use in the US.

C. Public Health Service Policy

The Public Health Service (PHS) requires that all institutions who wish to compete for and/or receive federal funds comply with the Public Health Service Policy on Humane Care and Use of Laboratory Animals (NIH, 2002). This policy is mandated by the Health Research Extension Act of 1985, known as Public Law 99-158, 20 November 1985, and incorporates the US Government Principles for the Utilization and Care of Vertebrate Animals Used in Testing, Research, and Training. The Office of Laboratory Animal Welfare (OLAW) is responsible for assuring that institutions comply with the PHS Policy. They do so by requiring institutions to submit an Animal Welfare Assurance to the OLAW for review, using the *Guide for the Care and Use of Laboratory Animals* (the *Guide*) (ILAR, 1996) as a basis for developing and implementing an institutional program for activities involving animals. Only after an Assurance has been reviewed and approved will individuals at the institution be permitted to compete for grant or contract funds from the US government. This is indeed an effective mechanism, and assures that all institutions receiving US financial support comply with US laws and regulations and an acceptable standard of animal welfare.

D. Good Laboratory Practices (GLPs)

The primary objective of the principles of GLP (Code of Federal Regulations, 1978; Office of the Federal Register, 1978) is to ensure the generation of high-quality practices and test data. They address laboratory animals only in that context, and then do so in performance standards only. Those general areas which affect laboratory animals are described much more directly in the PHS Policy, the Guide for the Care and Use of Laboratory Animals and the USDA regulations, and thus will not be discussed in great length under this section. Unique items specifically addressed and more strictly required under the GLPs are as follows:

(a) Separation of animal rooms or areas to ensure isolation of studies being done with test systems or articles known to be biohazardous, including volatile substances, aerosols, radioactive materials and infectious agents.

(b) Separation and isolation for housing of animals either known or suspected of being carriers of infectious disease agents.
(c) Separation of food and bedding storage areas from test systems compounds.
(d) More elaborate Standard Operating Procedures for housing, feeding, handling and care for animals and documentation of practices followed.
(e) More stringent identification procedures for test animals.
(f) Regular analysis of food, bedding, water and materials and documentation of such analyses.

While most of these do not directly address facilities, they do require facilities which are designed and managed to provide for the additional quality control measures.

E. Guidelines

Numerous guidelines exist for the care and use of laboratory animals, but none so visible and all encompassing as the *Guide for the Care and Use of Laboratory Animals* (the *Guide*) (ILAR, 1996). The *Guide* was first written by a committee of the American Association for Laboratory Animal Science (then called the Animal Care Panel) and published in 1963 with financial support and encouragement from the National Institutes of Health (NIH). Future editions were supported by the NIH and administered by the Institute for Laboratory Animal Research (ILAR). The National Academy Press, under the auspices of the National Research Council, published the seventh and current edition of the *Guide* in 1996, and planning is under way for a major update very soon. This single document serves as the "bible" for laboratory animal-care and -use policies and guidelines in the US. It is excerpted from and referenced in all major guidelines and regulations, and has been translated into and is being published in at least 12 other languages. Over 500,000 copies have been distributed throughout the world. The *Guide* is intended as an informative and voluntary document, but its practices are considered by many as best practices in laboratory animal medicine. Recommendations in the *Guide* require that facilities be designed, constructed and maintained to assure that acceptable standards of animal-care and -use practices are in place. The extensive bibliography in the *Guide* can be used as a reference when designing and constructing animal facilities, as should the entire document, but especially the chapter entitled "Physical Plant." The *Guide* recommends four major functional areas in an animal research facility, with space provided for (a) animal housing care and sanitation; (b) receipt, quarantine, and separation of animals; (c) separation of species or isolation of individual projects when necessary; and (d) storage. Tables with recommended space for most commonly used laboratory animals and some farm animals are provided in the *Guide*, as are recommended environmental temperatures for each animal species. The *Guide* serves as the primary reference document for the Association for the Assessment and Accreditation of Laboratory Animal Care International, which currently accredits over 740 animal-care and -use programs in over 30 countries. Compliance with the *Guide* is required for all institutions which wish to have an assurance with OLAW. *The Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching* (Federation of Animal Science Societies, 1999) was first published to address those animals which are not used in biomedical research and not covered by the *Guide*. A second edition was published in 1999, and a committee is currently working on a new edition. This document should be used when planning facilities for agricultural animals which are used in agricultural research.

F. International

Many large pharmaceutical companies have animal research facilities outside the United States, and sometimes wish to standardize policies and facilities throughout the company. Academic collaboration between research investigators frequently includes facilities and programs outside the United States as well. These and similar situations make it important that all collaborating work with animals adheres to a standard acceptable to all collaborators. The European Community has issued standards (European Union, 1986; Council of Europe, 2006) that are required in many participating countries and which may have an impact in collaborations with participating countries. The Canadian Council on Animal Care (CCAC) has published a two-volume series entitled the *Guide to the Care and Use of Experimental Animals* (CCAC, 1993/1994), which is used in the CCAC evaluation program. Other countries have various guidelines and regulations governing animal care and use which should be considered whenever collaboration in these areas is expected. Such relationships should be considered when designing animal facilities, and decisions should be made with as much information available as possible.

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Chapter 7

Environmental Considerations for Research Animals

Robert E. Faith and Michael J. Huerkamp

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I. INTRODUCTION

Biomedical research using animals has reached a very high level of sophistication. Over the years, compelling evidence has accumulated showing that numerous environmental variables can have profound effects on the biologic responses of research animals (Jonas, 1976; Vesell *et al*., 1976; Lindsey *et al*., 1978), with the potential for considerable confounding influence ultimately upon research (Crabbe *et al*, 1999; Bohannon, 2002a). The biologic response of the laboratory animal is the result of multiple genetic and environmental effects during the continuum from zygote to death (Lindsey *et al*., 1978) (Figure 7-1). Some of these factors, such as the ingredients in formulated diets, the enteric commensal bacterial flora, and even the genetic constitution of inbred strains, are prone to variability and potential drift. Given these consistency complexities and their not only unpredictable but also often furtive effects upon science, it is essential to control any variability that can be identified and reasonably achieved. From the animal resources program perspective, this is often most feasible at the facility operational level. Here, animal resources programs, with effective design and construction paving the way, can make the greatest fundamental contribution to the science enterprise by providing consistent environments conductive to well-being where the animals reside and are studied.

The environment as it relates to the research animal constitutes both a macro-environment and a micro-environment. The micro-environment of an animal is the physical environment immediately surrounding it (i.e., the cage or primary enclosure). The macro-environment is the physical environment of the secondary enclosure – the room or barn or pasture. In general, temperature, relative humidity, concentrations of gases and levels of particulate matter are higher in the micro-environment than in the macro-environment. The environmental factors contributing to variability in the micro-environment

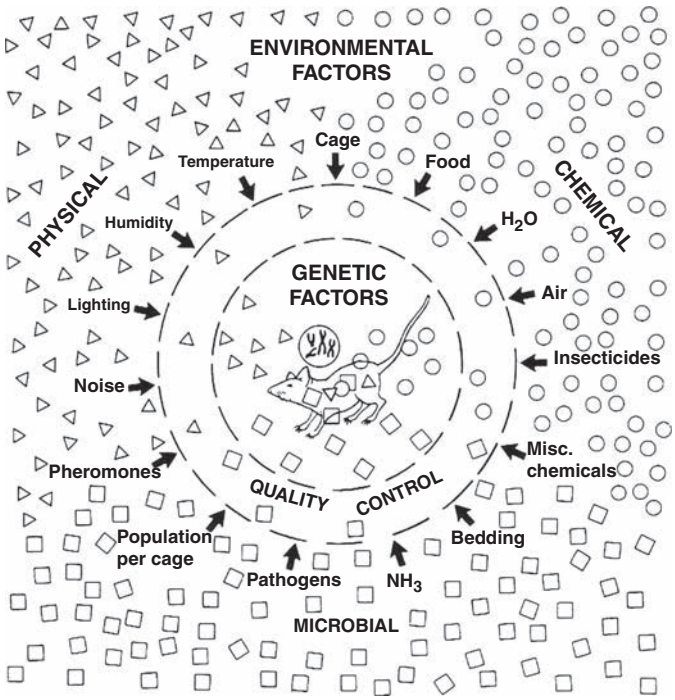

Fig. 7-1 The biological response of laboratory animals to experimental interventions may be profoundly influenced by multiple genetic and environmental variables that are illustrated in this figure from the first volume of *The Laboratory Rat*.

Reproduced from Baker *et al*. (1979), with permission.

and affecting animal health and well-being include cage design and construction materials, bedding material, use of filter tops on rodent cages, food and water, available living area, frequency of sanitation, air exchange and air quality (relative humidity, NH_3, CO_2, dust), temperature, light (intensity, photoperiod and wavelength), vibration, noise level (including ultrasound and infrasound), electrical and magnetic fields of force, pheromones, micro-organisms, parasites and pollutants (Newton, 1978; Clough, 1982, 1984), pesticides, chemicals, and even the stability and quality of the workforce. For example, the soundness of construction, such that vermin are effectively prevented from gaining access, will culminate in the use of fewer pesticides and other agents in proximity to research animals, not to mention precluding the risks of infection or infestation conveyed with vermin. The effects of environmental and husbandry factors on animal physiological and psychological function may be subtle, to the extent that effects are not observed, but perturb research results. This makes it extremely important that all reasonable steps be taken to control research variables, and emphasizes the need to define laboratory animals in terms of both genetics and environment (physical, chemical and microbial factors) and to report these crucial data in scientific publications.

Animals used for biomedical research should be kept under conditions that permit as standardized a response to experimental parameters as possible. Much evidence has accumulated over the years indicating that many environmental conditions can influence research results to a greater extent than is recognized by very many investigators (Clough, 1982; Crabbe *et al.*, 1999). Changes in the animal's external environment are perceived by exteroreceptors and relayed to the brain. If an environmental condition is sufficient to unbalance homeostasis, the neuroendocrine system is stimulated to operate to restore homeostasis (Clough, 1982). Good control of environmental factors can lead to a significant reduction in the variability of experimental results often seen between different laboratories, or even within the same laboratory (Roe, 1965; Golberg, 1974; van der Touw *et al*., 1978; Chvedoff *et al*., 1980; Crabbe *et al*., 1999). Innumerable factors can influence the response to experimental procedures. As directly influenced by facility design and renovation, these include temperature, relative humidity, air movement, light period, intensity and quality, sound, vibration, air pressure, water supply, gravity, electrical and magnetic fields, ionizing radiation, odors and fumes, other pollutants, and even micro-organisms, parasites, dust and chemicals (Newton, 1978; Clough, 1982). Provision of adequate control of environmental factors is paramount in the design and construction of new or renovated research animal facilities. Effective design allows for the operation of animal research facilities and delivery of a consistent standard of husbandry that minimizes variations that can modify an animal's response to experimentation. Temperature, humidity and ventilation are extremely important environmental variables. Together they determine relative heat loss or retention, and ultimately contribute heavily to metabolic rate.

This chapter will review environmental factors and their potential effects on animal research.

II. TEMPERATURE, RELATIVE HUMIDITY, POLLUTANTS AND VENTILATION

Current environmental standards for animal housing are based on room conditions, not conditions in the cage (the primary enclosure). The conditions in the primary enclosure (the micro-environment) may differ significantly from the room (macro-environment) conditions in factors such as dry-bulb temperature, relative humidity, gaseous content, and particulate concentrations (Woods, 1978; Baker *et al*., 1979; Clough, 1982, 1984). The differences between micro-environment and macro-environment will vary markedly between facilities. Complex interactions exist between production of heat and water inside the cage, and their dissipation into the macro-environment. Many factors may influence these interactions. These include the population density (Yamauchi *et al*., 1965), cage design (Serrano, 1971) and presence or absence of filter tops (Simmons *et al*., 1968; Besch, 1975), and the amount and velocity of air flowing over the cage (Woods, 1978; Reeb *et al*., 1998). The extent to which differences in micro-environment affect the responsiveness of animals to research

stimuli depends on the extent of the variations in micro-environmental factors, and on the ability of the animals to adapt to these environmental changes. At present, there is very little information available on the variation in experimental results caused by differences in micro-environmental conditions.

The relationship between the micro-environment and the macro-environment is not a simple one. A number of factors affect exchange between these environments. These include thermic isolation and air exchange, which are in turn determined by room ventilation intensity and pattern, and by cage type (plastic shoebox or wire grid), cage dimensions, and whether the cage is covered with a filter bonnet or not. When considering non-ventilated caging systems, cage ventilation rates are generally less than room ventilation rates. Cage type greatly influences this difference. Cage ventilation rates have been shown to be 82–92 percent of room ventilation rates for cages with wire-grid floors and 20–58 percent of room ventilation rates for shoebox-type cages (Murakami, 1971; Clough, 1984). Static micro-isolation cages (polycarbonate cages covered with filter bonnets) have been shown to have ventilation rates as low as 0.68 air changes per hour (Keller *et al*., 1989). The micro-environment is not solely determined by the room ventilation rate, but is also a function of the cage type and size, the animals housed in the cage and their activity level, the population density, bedding material, and cage-changing frequency. One study investigated the differences between room temperature and the temperature in cages as a function of where the cage was on the rack. The cages were wire-grid floor cages housing 4 rats per cage, and were located in a room that had 17 air changes per hour with a mean room temperature of 21.2°C and variation throughout the room of 1.4°C. In-cage temperatures varied with the height of the cage in the room. Cages on the top shelf were 4.9°C warmer than those on the bottom shelf, and in-cage temperatures were up to 5.7°C warmer than the "recommended environmental temperature" for rats (Clough, 1984). Other studies have recorded increases in cage temperatures and have reported that the in-cage temperature varies not only with the population density, but also with the construction material of the cage (Yamauchi *et al*., 1965; Murakami, 1971; Hirsjarvi and Valiaho, 1987).

Heat is one of the most important environmental factors affecting living organisms, and its effects have been extensively studied (Rose, 1967). Environmental temperature may affect food and water consumption, disease resistance, drug toxicity, and other biologic processes (Clough, 1982). Most research animals are homoeothermic mammals which generally keep their core body temperature at a steady value. The animal must maintain a fine degree of control over both heat production and heat loss in order to achieve homeothermy. Most laboratory animals can adapt to a wide range of environmental temperatures (10–30°C) (Weihe, 1965, 1971), provided that they are acclimated to the ambient temperature, the temperature does not fluctuate widely, and opportunities for behavioral temperature regulation are provided. However, because the thermal neutral zone of an animal is strongly dependent on the physical environment, an animal's thermal neutral zone may vary in different experimental set-ups (Romanovsky *et al*., 2002). Metabolic adaptation can commence within minutes (Clough, 1982) but continues for varying periods, depending on the animal's previous experience and the extent of the temperature change. Complete adaptation commonly takes 2–3 weeks in rats (Gelineo, 1934), but can take 5–6 weeks (Sellers, 1957) or even 7–12 weeks (Depocas, 1960); therefore, sudden fluctuations in temperature should be avoided. Changes in the ambient temperature cause changes in the metabolic rate of the animals (Svendsen, 1994), and affect enzyme activity (Shysh and Noujaim, 1972) and the toxicity of or response to drugs and chemicals (Balazs *et al*., 1962; Weihe, 1973; Sanvordecker and Lambert, 1974; Clough, 1982).

In the controlled environment of the research animal facility, the core body temperature will be higher than that of the air around the animal. Thus, there is a temperature gradient from the central parts of the body, through the superficial layers, to the surrounding air. Homoiotherms are generally considered to consist of a core and a shell (Verbiest, 1956). Obviously, ambient temperature significantly affects this gradient. Changes in the temperature gradient and thickness of the shell are more significant in hairless animals, and are particularly noticeable in the limbs and tail. There is an increase or decrease of 20–30 percent for each 1°C rise or loss in ambient temperature in the speed of many tissue and cellular functions (Irving, 1964). Thus, the absorption and/or activity of any substance given epicutaneously, subcutaneously or intramuscularly are likely to vary with ambient temperature. Changes in ambient temperature are compensated for by one of several methods. These include increases or decreases in: metabolic rate, activity (including shivering), non-shivering thermogenesis, peripheral circulation, insulation (e.g., fat or fur) and evaporative loss (e.g., sweating and changes in respiratory rate (panting). Also included are the use of so-called behavioral thermoregulatory activities, such as: changes in the ratio of surface area to mass (huddling or extension of limbs – including the tail), voluntary variation in the extent of external insulation (nest-building), and selection or creation of a less thermally stressful habitat (shelter- and shade-seeking, nest-building). In non-sweating species such as rodents, increases in ambient temperature result in increases in respiratory rate (Clough, 1982). The main physiological response of rodents to changes in ambient temperature is alteration of their metabolic rate (Weihe, 1971).

A range of 20–26°C (68–78°F) has been shown to be the optimal temperature range for rat rooms (Yamauchi *et al*., 1981). Exposure of male rats to high ambient temperatures (89–90°F, 31.6–32.5°C), such as may happen with air conditioning failure in hot weather, may result in irreversible testicular atrophy, or even death (Pucak *et al*., 1977). Transient ambient temperature spikes in excess of 30°C have been shown to cause embryonic mortality and teratogenesis in mice (Bellve, 1972, 1973), and to accelerate the phototoxic effects of bright

lighting (Organisciak *et al*., 1995). Thermoregulatory mechanisms were altered in rabbits from dams kept for 14 days prepartum, and then subsequently reared under continuously warm conditions (33°C) (Cooper *et al*., 1980). Likewise, marked environmental temperature deviations, including only transient excursions above 30°C or down to 10°C, can influence the age of rodent weaning (Gerrish *et al*., 1998). Songbirds kept at temperature extremes of 5°C and 30°C show retarded and enhanced gonadal regression, respectively, as compared to those housed at 20°C (Wingfield *et al*., 1997). Lactation is impaired in rats exposed to high temperatures (Benson and Morris, 1971; Yagil *et al*., 1976). Changes in ambient temperature can modulate immune function. Cold stress has been shown to decrease antibody production (Sabiston *et al*., 1978), while heat stress results in elevated corticosteroid levels, changes in lymphocyte migratory patterns, a decrease in thymus and spleen weights, an increase in the phagocytic index, and a decreased antibody response (Krynicki and Olszewski, 1989; Joseph *et al*., 1991; Yamamoto *et al*., 1999). Lowered temperature (20°C vs 25°C) inhibits hepatic microsomal enzymes (HME) and prolongs hexobarbital sleep times in mice (Vesell, 1968). The range of environmental temperatures at which an animal's oxygen consumption is minimal and virtually independent of changes in ambient temperature is the *thermoneutral zone*. It appears that the temperature that animals are acclimated to affects the thermoneutral zone of the animal and alters the set-point temperature around which thermal responses are regulated (Gwosdow and Besch, 1985). Although maintaining general temperature consistency within the *Guide for the Care and Use of Laboratory Animals* (the *Guide*, ILAR, 1996) ranges has served the animal research enterprise seemingly well, it is noteworthy that mice tend to prefer higher ambient temperatures as they age, and warmer temperatures during daylight (28–29°C) and cooler (23–24°C) temperatures during the dark (active) period (Gordon *et al*., 1998).

Sources of heat within an animal room include fluorescent lights, motorized blowers on ventilated caging systems (VCS), mobile electrically-powered Class II-type workstations, stationary biosafety cabinets (BSC), animal-care and research personnel and, obviously, the animals themselves. A beagle-sized dog (10 kg) will dissipate approximately 260 BTU/hour (77 watts) of sensible and latent origin into the environment (Woods *et al*., 1975). A single mouse will generate 1–2 BTU/h (Walker, 1967; Gates *et al*., 2005). A colony of 400 mice in a 1,000-ft^3 room receiving 10 complete air changes per hour will generate sufficient heat liberated by radiative, conductive, convective and evaporative processes to raise the room ambient temperature by 2–4°F. Micro-environmental temperatures within mouse cages, including those that are individually ventilated, tend to range between 0.5 and 1.5°C and sometimes up to 3°C (depending upon the macro-environment, population density, sampling methodology and other factors), above the ambient macro-environmental temperature (Simmons *et al*., 1968; Corning and Lipman, 1991; Lipman *et al*., 1992; Huerkamp and Lehner, 1994; Clough *et al*., 1995; Perkins and Lipman, 1995).

The position of racks, cages and pens in any room may affect the effectiveness of ventilation by obstructing airflow patterns and creating eddies, areas of recirculation, unventilated zones, and conditions of air retrainment (Morse *et al*., 1995; Hughes and Reynolds, 1997), resulting in room-wide variations in gas concentrations and thermal gradients. To allow for the most favorable airflow, enabling thorough ventilation of the full space, and to optimally maintain thermal consistency through all three dimensions of a room, the principles of computational fluid dynamic (CFD) modeling should be employed in design (Hughes and Reynolds, 1995, 1997; Morse *et al*., 1995; Hughes *et al*., 1996; Curry *et al*., 1998). CFD is a computational technology that enables the study of the dynamics of things that flow. A model of the system or device to be studied can be built with CFD. The fluid-flow physics and chemistry are applied to the virtual prototype, and the software will output a prediction of the fluid dynamics and related physical phenomena. CFD software provides the power to simulate flows of gases and liquids, heat and mass transfer, moving bodies, multiphase physics, chemical reactions, fluid–structure interactions and acoustics through computer modeling. CFD software allows the development of a "virtual prototype" of the system or device to be analyzed, and then applies real-world physics and chemistry to the model. The software provides images and data, which predict the performance of the design.

The goal in design should be to control the temperature to a set point within a broad range of possibilities, and manage variability around the mean as tightly as possible. Specifically, temperature should be controllable in each housing room independently within a range of 59–85°F and ±1–2°F of the set point the year round. While most research animals can be maintained at a set temperature somewhere in the range of 64–79°F, the ability to deliver a range of temperatures consistently is important. For example, female *Xenopus* frogs in production, and rabbits, benefit when kept in thermal environments toward the lower extreme. Likewise, other animals, such as zebra fish, are most optimally kept at the high end of the range. The optimal temperature condition for moderately active work done by humans varies from 64–73°F, which lies conveniently within the *Guide* recommendations for most species and can be realized without special accommodation (see Chapter 12). Staff working at temperatures outside of the optimal range will be prone to fatigue and decreased productivity. Room temperatures should be monitored with surveillance and alarming technology capable of alerts at extremes when animal well-being or science may be imperiled. There is no consensus on where to locate sensors. Assuming complete mixing of air within the room, temperature sensors may be placed in room exhaust ducts. When animals are housed in VCS connected directly to the exhaust, sensors in the exhaust provide a truer indication of the conditions in the cages than do sensors in the room. In this case, control of room temperature from sensors

in the exhaust allows for provision of more closely controlled temperatures in the cages.

Relative humidity (RH) inside the cage tends to be higher than that in the room due to water output by the animals in the cage. Animal well-being is affected by ambient RH. RH affects the thermoregulatory capacity of animals, and affects control and management of airborne diseases (Clough, 1982). High RH in the cage encourages the production of NH_3 by urease-positive bacteria. It also facilitates mold growth on feed, but at high and otherwise counterproductive levels (>50 percent) it suppresses aeroallergens (Edwards *et al*., 1983). For rodent housing, it has been shown that room air exchange rates of 12–16 ac/h are required to keep in-cage (in open cages) RH from rising above 70 percent when the RH of the supply air is 45 percent, and when the calculation was based on respiratory water only. When the calculations are based on total water turnover, the room ventilation rates need to be between 44 and 87 ac/h to keep in-cage RH from rising above 70 percent. If the RH of the supply air is 60 percent, the room ventilation rates may need to be as high as 200 ac/h to control in-cage RH (Clough, 1984). Current standards (10–15 ac/h) for room ventilation rates appear not to be excessive in light of these calculations, and in fact may be low. These data also indicate that in high-humidity climates, dehumidifiers may be required in conjunction with the HVAC system to control humidity.

Excessively high or low humidity can have negative impact on research animals. Extremes in relative humidity can affect food consumption (Guerrini, 1981), activity (Clough, 1982), postnatal development (Drickamer, 1990), transmission of infectious agents (van der Veen *et al*., 1972) and transcutaneous absorption of drugs (Clough, 1982). Variations in relative humidity appear to be less significant at low dry-bulb temperatures than at high ones (Clough and Gamble, 1976). For many animals evaporation is the main method of heat loss, and, when ambient temperature reaches the body temperature of the animal, evaporation is the only available means of heat loss. When relative humidity is high, evaporative heat loss from the animal is either absent or severely impaired. Low humidity leads to increased levels of dust and increased susceptibility to upper respiratory tract infections (Baetjer, 1968; Clough and Gamble, 1976). Low humidity can also lead to ringtail – a scaliness, annulation and reddening of the tail tip, and necrosis – in rats (Njaa *et al*., 1957; Flynn, 1959), hamsters (Stuhlman and Wagner, 1971) and domestic and exotic mice (Nelson, 1960; Ellison and Westlin-van Aarde, 1990). Generally thought only to be a problem at RH < 30 percent, ringtail has been observed in rat pups kept under 45–65 percent relative humidity and possibly caused in combination with dietary factors or predisposed by genotype (Crippa *et al*., 2000). It is seen, for example, every winter in modern animal facilities at the Medical College of Wisconsin.

By regulatory standard, relative humidity should be controlled within a range of 30–70 percent (ILAR, 1996), and optimally within 10 percent of the set point on a year round basis. Relative humidity control may be done at the room level or on a zonal basis within the animal research facility, and should be monitored with an alert capability when extremes greater than 70 percent or less than 30 percent occur. As with temperature, relative humidity sensors may be located in the room or in exhaust ducts. In the case of VCS connected directly to room exhaust, humidity sensors in the duct, when used to control room humidity, allow for provision of more closely controlled humidity in the cages. To retard ammonia production while also attempting to prevent ringtail lesions, RH for rodents should be kept at 40–50 percent. For aquatic species, such as tropical fish, RH at high extremes may be desirable, and may be unavoidable given the nature of the humid room environment. The RH comfort range for work by humans is 20–70 percent (see Chapter 12).

Ammonia is one of the most common and abundant gaseous pollutants associated with the husbandry of research animals. It is converted from urea by urease-producing bacteria ordinarily found in the feces and coming inevitably in contact with urine in the bedding and cage pans. In rodents chronically exposed to ammonia at consistent levels that commonly occur in these cages (e.g., 25–100 ppm) the following have been observed: enhanced incidence and severity of respiratory infections (Broderson *et al*., 1976), impairment of mucociliary activity (Dalhamn, 1956), depressed immune function (Targowski *et al*., 1984), and altered hepatic microsomal enzyme activity (Vesell *et al*., 1973). Chronic exposure of rodents to as little as 10 ppm ammonia has been shown to have a biological effect in terms of reducing oxygen consumption and increasing blood catalase levels (Mikhaylov *et al*., 1964). While previously thought by some to be important, persistently low or intermittently excessive ammonia concentrations (transient spikes to 200–300 ppm) in cages, and as encountered typically in research colonies, do not seem to have much effect on the behavior, immunology, biochemistry and physiology of experimental rodents (Reeb-Whitaker *et al*., 2001), or on mothering performance, neonatal survival or weanling growth (Huerkamp *et al*., 1994; Reeb-Whitaker *et al*., 2001). Exposure to ammonia, however, may confound inhalation toxicology studies (Bolon *et al*., 1991). Managing macro-environmental ammonia levels contemporarily may be most important from a worker safety and comfort perspective. Regular exposure of husbandry and research personnel, particularly those working with rodents, to macro-environmental ammonia concentrations in excess of 25–35 ppm will be non-compliant with established workplace standards (ACGIH, 2001). Most approaches to ammonia control are related to husbandry procedures, particularly the frequency of sanitation, selection of contact bedding and ventilation of individual cages.

The exposure of animals, particularly rodents, to concentrations of carbon dioxide in excess of ambient levels in the micro-environment is a research variable of unknown, but probably inconsequential, significance. Carbon dioxide is a byproduct of aerobic respiration, and is removed from

indoor environments by ventilation. Within mouse cages, carbon dioxide levels range from 1,000–6,000 ppm in those covered by filter tops (Huerkamp and Lehner, 1994; Krohn and Hansen, 2002), 900–2,000 ppm in open cages (Serrano, 1971; Huerkamp and Lehner, 1994; Perkins and Lipman, 1995), and approximately 2,000 ppm in ventilated cages (Huerkamp and Lehner, 1994; Perkins and Lipman, 1995; Reeb, 1998). These values are significantly greater than the macro-environmental value of 300–500 ppm. The effect of chronic exposure to carbon dioxide concentrations in excess of 500 ppm on animal biologic processes and the implication for research results is not known. Carbon dioxide is a respiratory stimulant at concentrations up to 100,000 ppm (10 percent), but does not pose risk as an asphyxiant until concentrations approach or exceed 40 percent (Lumb and Jones, 1984). In nature, tunneling rodents may be acclimated to ambient carbon dioxide concentrations of up to 14,000 ppm (Studier and Bacce, 1968). Rodents exposed to 30,000 ppm CO_2 have been shown to have increased corticosterone levels consistent with distress (Krohn and Hansen, 2000). The TLV for continuous safe human exposure to carbon dioxide for 40 hours per week has been established at 5,000 ppm, with a maximal 30,000 ppm safe exposure for 15 minutes (ACGIH, 2001). At chronic carbon dioxide exposures of 6,000 ppm or less, such as those found in mouse cages, the risk of asphyxiation from even oxygen displacement is non-existent, but the effect on mouse physiology is not clear. In the case of power failures for ventilated caging systems, carbon dioxide levels in mouse cages may increase to 80,000 ppm in 1–2 hours (Hoglund and Renstrom, 2001; Krohn and Hansen, 2002).

Rather than carbon dioxide intoxication, the greatest risk for compromised research or animal lethality is air supply failure, particularly in ventilated cages, resulting in insufficient available oxygen to support life. In a controlled study of a rat ventilated-caging system, oxygen levels plummeted to lethal levels of less than 10 percent in 30–60 minutes in cages with dams and nursing pups when an air-supply power failure was simulated (Huerkamp *et al*., 2000). This affirms the need for redundant emergency power to ensure animal life support where ventilated caging systems are used. Other gaseous pollutants of seemingly little significance that may be found in the research environment include methane (Huerkamp and Lehner, 1994), acetic acid (Perkins and Lipman, 1995), hydrogen sulfide (Broderson *et al*., 1976) and sulfur dioxide (Perkins and Lipman, 1995).

Room ventilation functions to supply adequate oxygen; remove heat loads caused by animal respiration, lights, and equipment; dilute gaseous and particulate contaminants; adjust room RH; and create static-pressure differentials between adjoining spaces where appropriate. Prior to the 1996 revision, the *Guide* recommended room ventilation rates of 10–15 fresh air changes per hour. In the 1996 revision the recommendation became a performance standard recommending that the ventilation rate be the minimal required to control the heat load expected to be generated by the largest number of animals to be housed in the room in question, plus any heat expected to be generated by non-animal sources and heat transfer through room surfaces. This allows for flexibility in the use of existing space and in the design of new space. This type of approach can be used to determine the maximum number of animals that can be housed in an existing space with a fixed rate of ventilation. In addition to controlling heat loads, ventilation rates must be sufficient to control odors, allergens, airborne particulates, metabolically generated gases, etc. (ILAR, 1996). This may require ventilation rates beyond the calculated minimum based on heat load.

Depending upon an individual's medical history, the risk for animal workers to develop allergies to laboratory animals after sufficient exposure ranges from 10 to 70 percent (National Research Council, 1997). While room ventilation is effective for controlling temperature, relative humidity and gaseous pollutants, it is significantly ineffectual in the management of particulates (Reeb-Whitaker *et al*., 1999). Since rodent allergens are carried on large particulates (>5.8 microns) (Hollander *et al*., 1998), increased room ventilation rates will not effectively reduce allergen exposure (Kacergis *et al*., 1996; Hollander *et al*., 1998) unless air change rates exceed 60 air changes per hour (Swanson *et al*., 1990; Hunskaar and Fosse, 1993). The bedding of laboratory animals may contain other biologically effective compounds, such as bacteria, fungi and endotoxins, and these may be distributed into the ambient air depending on the relative dustiness of the bedding material (Kaliste *et al*., 2004). The mere use of filter tops on rodent cages will reduce aeroallergens 10-fold in the macro-environment (Sakaguchi *et al*., 1990; Hollander *et al*., 1998), but this benefit is negated if animals are handled or cages are serviced without additional measures (Hollander *et al*., 1998). Housing rats in open cages but inside chamber units with HEPA filtration reduced airborne Rat n1 antigen levels by approximately 50 percent (Ziemann *et al*., 1992). As such, the most effective approach to allergen management in rodent rooms is to use ventilated caging systems operated under negative pressure and with HEPA filtration of exhaust air, and supported by the use of ventilated changing tables (e.g., Class II-type mobile BSC) when cages must be opened. This has been shown to reduce ambient mouse allergen (Mus m1) concentrations 10- to 250-fold in the macro-environment compared with situations where mice were housed in uncovered cages and an open surface was used for cage-changing (Gordon *et al*., 1997, 2001; Reeb-Whitaker *et al*., 1999; Schweitzer *et al*., 2003; Platts-Mills *et al*., 2005). In suites devoted to flexible film isolator use, aeroallergens have also been shown to be rare (Gordon *et al*., 2001). Incidentally, although not a component of design, the use of ground-corncob contact bedding for rodents has been associated with greater than 50 percent reductions in aeroallergens as compared to wood shavings (Sakaguchi *et al*., 1990). It is likewise noteworthy that cleaning mouse rooms at an accelerated frequency also has no effect upon ambient Mus m1 concentration (Schweitzer *et al*., 2003). Other design considerations to prevent allergies should be aimed at protecting persons

with jobs not involving animal use (e.g., administrative and custodial personnel) from direct or indirect animal contact. In large, complex research buildings, this involves animal facility security, proper ventilation and, where institutional practices allow animals to be transferred between housing sites and laboratories, sufficient numbers, distribution and security of service elevators and laboratory corridors.

For small rodents, such as rats and mice, design can enable management of ammonia, carbon dioxide, water vapor, and heat loads at the cage level through facility accommodations enabling the use of ventilated caging systems (VCS). Whether actively supplying and/or exhausting air via motorized blowers or through convection principles, these housing modalities combine filter tops with ventilation at the cage level, providing 30–100 air changes per hour (Hasegawa *et al*., 1997; Lipman, 1999; Rivard *et al*., 2000). Rodent cages with filter tops tend to have micro-environmental RH levels ranging from 5–25 percent above the ambient macro-environment (Simmons *et al*., 1968; Huerkamp and Lehner, 1994; Perkins and Lipman, 1995). VCS, however, are useful in muting this elevation and promoting a drier micro-environment (Lipman *et al*., 1992; Huerkamp and Lehner, 1994). While promoting stabilization of environmental conditions (Corning and Lipman, 1991; Lipman *et al*., 1992; Huerkamp and Lehner, 1994), VCS also facilitate labor savings that would otherwise be expended on cage-changing (Huerkamp and Lehner, 1994), prevent airborne microbial transmission (Huerkamp, 1993; Lipman *et al*., 1993; Macy *et al*., 2002) and, where the exhaust is ducted directly out of the animal room, remove allergens (Renstrom *et al*., 2001; Schweitzer *et al*., 2003) and heat generated by the animals. A sometimes unappreciated cost related to animal care is the increased burden on the HVAC system to manage heat released into the space from animals, humans and equipment, the subsequent thermal variability, and even elevations causing worker fatigue and impaired productivity. Higher air-change rates in a room also demand more electricity and more mechanical space, often with a net loss of program space within the overall context of the building. Exhausting directly from the rack into the facility duct system reduces room aeroallergens, heat load and noxious gas concentrations (Hoyt and Goldsteen, 1998) (Table 7-1). VCS also enable less intensive cage-changing. The mortality of nursing mouse pups was shown to be significantly higher when lactating dams and suckling pups were transferred to a clean cage every week rather than every 14 days (Reeb-Whitaker *et al*., 2000). Frequent cage-changing may be detrimental when pheromones are essential for reproduction. Less frequent cage-changing is also desirable, as moving rodents from a soiled to

TABLE 7-1

THERMAL LOAD MODELING[1] IN A RODENT HOUSING ROOM (VOLUME 3780 CUBIC FEET) SHOWING SENSIBLE HEAT LOADS AND ROOM TEMPERATURES RELATIVE TO UTILITIES, MAXIMAL RODENT POPULATION, HUMAN ACTIVITY AND SEGREGATED BY RATE OF VENTILATION

Condition	Contributing BTU/h[2]	Sum BTU/h[4]	Room temperature (°F)[3]	
			10 ACH[5]	15 ACH
Empty	0	0	59	59
Fluorescent lights on	3,150[6]	3,150	63.6	62.1
Ventilated caging system[7]	3,672[8]	6,822	69.0	65.7
Populated with mice	4,662[9]	11,484	75.9[10]	70.3
Cage changing procedures	2,906[11]	14,390	80.1[10,12]	73.1
Duct VCS exhaust from room	(6,498)[13]	7,892	70.6	66.7

[1]Modeling data and calculations kindly provided by W. Freeman and M. Mottet, Atlanta, GA, 1999.
[2]BTU = British Thermal Units.
[3]Formula for room temperature: T = EAT + [BTU/h÷(1.08 × CFM)], where EAT = entering air temperature (59°F) and CFM = air supply rate in cubic feet per minute (630 cfm = 10 ACH; 945 CFM = 15 ACH).
[4]Value in each row represents the sum total of all contributing BTUs.
[5]ACH = air changes per hour.
[6]Installed lights generate 3,150 BTU/h (W. Freeman and M. Mottet, personal communication, CUH2A, Atlanta, GA, 1999).
[7]Data based upon ventilated caging system (VCS) with 6 racks, 140 cages/rack (unoccupied) and dual exhaust and supply blowers.
[8]3672 BTU/h from 12 motorized blowers on 6 racks (Laboratory Products, Inc., Seaford, DE, 1999).
[9]Data based upon 6 racks with 140 cages/rack and 6 mice/cage given 1.1 BTU/mouse/h (see: Walker, 1967).
[10]Temperatures exceeds maximum recommendation of 74°F for humans engaged in moderately active work (Anonymous, 1996).
[11]Data based upon use of mobile Class II-type workstation producing 2156 BTU/h (Laboratory Products, Inc., Seaford, DE, 1999) and used by two animal-care technicians emitting a sum 750 BTU/h (1997 *ASHRAE Fundamentals Handbook*, ASHRAE p 28.8).
[12]Temperature exceeds maximum dry-bulb allowance for mice of 79°F (*Guide*,1996).
[13]Connecting rack air effluent manifold to room exhaust duct and removing six exhaust blowers reduces the BTU load by 1,836 per hour. Model also assumes exhausting all mouse-generated BTU (4,662 BTU).

clean cage may transiently increase core body temperature (Kozak *et al*., 1994), increase corticosterone levels (Denda *et al*., 2000), cause transient hypertension and tachycardia (Duke *et al*., 2001), and alter skin-barrier permeability in hairless mice (Denda *et al*., 2000). Equipment purchase, filter maintenance and, where blowers are motorized, electrical power are significant upfront and lifetime costs of VCS. Electrical circuitry for the animal quarters should be sufficient to simultaneously power all outlets, and be connected to emergency power sources. Stray voltage is a theoretical concern with use of VCS, but has not been demonstrated to be a problem.

The ventilation rates for various spaces within the facility should be adjusted so that clean spaces are positive in pressure to dirty spaces. From an environmental management perspective, pathogen-free animal housing areas, for example, should be under relative positive pressure in relation to potentially contaminated areas. In modern facilities with cage-level barriers and sporadic (rather than widespread) rodent infectious diseases, the management of animal odors and the containment of allergens generally assume greater weight. In many cases, facility operations take a pragmatic approach and keep animal housing areas under negative relative pressure to corridors. Sites for quarantine, isolation and biohazard usage clearly should be negative in air pressure relative to hallways, corridors and other uncontaminated areas. It is useful to monitor directional airflow and air pressure, particularly in these areas. In the end, the ventilation system should allow ready conversion of any room back and forth between positive and negative air pressure and be equipped with dampers and other seals, permitting rooms to be sealed for decontamination.

III. LIGHT

Light is an important part of an animal's environment, and intensity, quality and photoperiod are variables that can influence biological response, including physiology, morphology and behavior (Bellhorn, 1980). Unlike HVAC failures, lighting malfunctions are rarely life-threatening, but they rank among the greatest perils to science. While many scientists may accept some variability inherent to temperature or relative humidity control, lighting arguably is the parameter where unwavering consistency is most critical. Fluctuations in photoperiod, in particular, can play havoc with research. Potential photostressors include light intensity, spectral quality, or photoperiod inconsistencies or failures. One of the best known responses to light is the retinal degeneration that occurs in albino rodents, especially rats, as a consequence of exposure to light (O'Steen and Anderson, 1972; Bellhorn, 1980; Semple-Rowland and Dawson, 1987a, 1987b). Sprague-Dawley rats raised for 15 weeks in a 12L/12D cycle at a light intensity of 6 lux and then exposed to a light intensity of 270 lux in a 12L/12D cycle develop severely damaged retinas within 3 to 7 days. It has been shown that Lewis and Buffalo rats are more susceptible to retinal photic injury than are Wistar and Fischer rats (Borges *et al*., 1990). Pigmented strains appear to be less susceptible (Reiter, 1973), but may experience photic injury (Williams *et al*., 1985). Chronic stress increases susceptibility to retinal damage (O'Steen and Brodish, 1985). The damaging effects of bright light can be exacerbated in combination with environmental temperature elevations. Rats exposed to 1100 lux and 34.5°C for 1.5 hours showed 50 percent visual cell loss, with the same degree of visual cell loss occurring after only 1 hour when rats were maintained at 37°C (Organisciak *et al*., 1995). Continuous exposure to relatively dim light (110 lux) for as few as 7 days has also been shown to be phototoxic for rats (Noell and Albrecht, 1971). Under practical conditions, the intensity of light illuminating top-tier rodent cages may be 3–19 times greater than that reaching the bottom tier of a rack (Clough *et al*., 1995).

The material that the cage is constructed from plays a major role in the amount of light that an animal is exposed to, with clear, translucent cages allowing the most light into the cage. With cage types that are placed on racks, the position of the cage on the rack is important because light intensity decreases with the square of the distance from the light source, and upper cages and shelves block light from lower cages. For rooms with the light source at the ceiling, light at the top shelf of a rack may be 80 times more intense than at the bottom shelf (Weihe, 1976). For photoperiodicity, rats must perceive at least 5–10 lux (0.5–1 foot-candle) during the light period, and dim (less than or equal to 0. 15–0.2 lux) light at night (Lynch, 1988), remembering that in nature most rodent species spend their daylight hours largely sheltered from light and are adapted to live in poorly illuminated environments. Contamination with as little as 0.2 lux light exposure during the dark cycle can alter circadian rhythms (Minneman *et al*., 1974). In cancer studies involving rats, dim light (0. 25 lux) during the dark cycle has been shown to alter melatonin cyclicity to the degree to enhance oncogenicity (Dauchy *et al*., 1999).

Certain common mouse genotypes, such as those of ICR, C3H and FVB lineage, carry retinal degeneration (rd) genes and have impaired visual acuity commonly from early onset retinal degeneration (Iseki *et al*., 1989; Balkema and Drager, 1991; Gimenez and Montoliu, 2001; Adams *et al*., 2002). Sufficient intensity during the light phase can be attained inside tinted thermoplastic cages, providing the macro-environmental light intensity is at least 100 lux (about 10 foot-candles) at the cage front (Figure 7-2). However, hypopigmented rodents (albino, beige, pale ear strains) have higher visual thresholds than do pigmented genotypes (Balkema and Drager, 1991). During periods of darkness, controlling levels of perceived ambient light to less than 0.20 lux should be the design goal.

Light is a powerful stimulant and synchronizer of the reproductive system biological rhythms. Photoperiodicity affects reproductive performance in a variety of species, including many types of freshwater and marine fishes (Crim, 1982; Peter, 1982), birds (Wingfield *et al*., 1997), and rodents

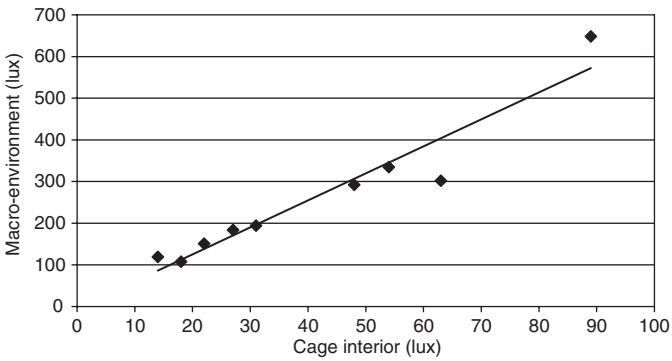

Fig. 7-2 Light intensity (lux) scatter plot and regression line as measured in polyphenylsulfone thermoplastic cages in comparison to ambient macro-environmental light (lux) immediately outside the cage using a digital illuminometer (Model 93-1065F, BEHA Group, Glottertal, FRG).

Figure compliments of Michael J. Huerkamp.

(Heideman and Sylvester, 1997). The intensity of lighting also influences reproduction. For example, increased light intensity prolongs the estrous cycle and the period of vaginal cornification of mice and rats (Piacsek and Hautzinger, 1974; Donnelly and Saibaba, 1993). In rats the estrous cycle lasts 4 days with a 12L:12D cycle and 5 days with a 16L:8D cycle; with a 22L:2D cycle the estrous cycle becomes irregular and the animals will not reproduce (Svendsen, 1994). Growing female rats show accelerated maturation when born and raised under continuous lighting (Piacsek and Hautzinger, 1974), while adult female rats housed in continuous light display persistent vaginal estrus and perturbations of 17 beta-estradiol and estrone levels (Takeo, 1984; Cvijic *et al*., 1997–1998). The age of vaginal opening of rats is inversely related to light intensity, with fewer days required to attain maturation at higher intensity. For example, rats kept under 14:10 light:dark cycles matured 2 days earlier when kept under 100 lux as opposed to 30 lux during the day cycle (Piacsek and Hautzinger, 1974). Ovarian weights of maturing female rats increase directly and significantly with light intensity (Piacsek and Hautzinger, 1974). Constant exposure of rats to light results in a significant increase in plasma ACTH, an increase in epinephrine synthesis in the adrenal glands, significantly reduced concentrations of dopamine and norepinephrine in the hypothalamus, and an increased concentration of serum progesterone (Ivanisevic-Milovanovic *et al*., 1995). Very short periods of light occurring during the dark phase can have significant effects on physiology (Clough, 1982). Exposure to light in the dark period suppresses endogenous melatonin levels, which in turn may contribute to certain disease states (Reiter, 2002). Therefore, lights should not be turned on during the dark phase of the light cycle unless it is absolutely necessary. If light is absolutely necessary in the dark cycle, it should be of a wavelength that the animal does not see. Room-light timers should be checked on a regular basis to assure that lights are cycling correctly. It has been said that rodents do not see red light, but it has been shown that continuous red light induces persistent estrus in female rats (Lambert, 1975). This is most likely a pineal effect. A study conducted in Finland with people showed that an increase in photoperiod significantly increased conception rates and decreased the incidence of uterine hyperplasia (Luce, 1971).

Photoperiod has a profound regulatory effect on circadian rhythms (Hastings and Menaker, 1976) and, by extension, myriad biological processes. Photoperiod affects the levels of production of hormones from a variety of organs. It is at least partially responsible for the control of adrenal hormone cycling (Luce, 1971), electrolyte-regulating enzyme activity levels (Zaugg, 1981) and anabolic activity of the brain, including brain protein synthesis (Shapiro *et al*., 1981). The ratio of light-to-dark influences redox enzyme activity in the central nervous system, drug metabolism, and drug toxicity (Radzialowski and Bousquet, 1968; Nair and Casper, 1969; Jori *et al*., 1971; LeBouton and Handler, 1971; Chedid and Nair, 1972; Baran *et al*., 2000; Pozdeyev and Lavrikova, 2000). Photoperiod also affects body temperature (Fioretti *et al*., 1974) and locomotor activity (Besch, 1969). The light–dark cycle influences immune function, exemplified by the fact that humoral and cellular immune responses to thymus-dependent antigens, levels of circulating lymphoctes, and cytokine production have a circadian rhythm (Kawate *et al*., 1981; Hayashi and Kikuchi, 1982; Fernandes *et al*., 1984; Sletvold *et al*., 1988; Li and Xu, 1997; Ohdo *et al*., 2000; Pelegri *et al*., 2003). Male mice housed in continuous light for 1 week showed much higher levels of corticosterone and shorter agonistic latency than animals housed with a 12:12 light–dark cycle (van der Meer *et al*., 2004). Phase shift in the light–dark cycle results in suppression of the immune response to thymus-dependent antigens (Hayashi and Kikuchi, 1985). Rodents kept under continuous lighting, irregular lighting schedules or light-contaminated dark phases have been shown to have altered rates of neoplasia or infectious disease as compared to controls under light and dark cycles of consistent fidelity (McEachron *et al*., 1995; Dauchy *et al*., 1997; Blask *et al*., 2002, 2003). Immune function has been shown to be enhanced in songbirds kept under short light cycles as opposed to long days (Nelson and Demas, 1996), but the same phenomenon apparently does not hold true for chickens (Campo and Davila, 2002).

Much less is known about the effect of phototransition, and we tend to neglect this variable in the environment of research animals; however, phototransition may have significant effects on biological processes. Sudden changes from light to dark or from dark to light without twilight are startling, and leave little time for physiological or behavioral adjustment (Allen, 1980). Birds not acclimated to the photoperiod, housed in flight cages and taking to wing, for example, may be prone to collisions with walls, perches or other birds upon abrupt extinguishment of light. It is known that phototransition affects activity sequences in many species of freshwater and marine fish (Helfman, 1979, 1981). These activities appear to be related to

particular intensities of light that occur in the natural transition from light to dark. The activities have more than incidental impact on the survivability of the fish. These activities include feeding behaviors, social distance determinations, parasite cleaning activity, and comfort behaviors, and in some species many of the behaviors are specific to the time of phototransition and are achieved only during this period. Instantaneous change from dark to full lighting intensity may have a much greater impact on the biological and physiological well-being of a captive animal than a simple startle response at the transition. It appears that improper transition may eliminate important activities, or modify them into ineffective parodies of the original behavior (Stoskopf, 1983). Animals exhibit many interesting behaviors which occur during the crepuscular periods or in dim light which may not be expressed in a sudden on–total-off light cycle (Allen, 1980).

There have not been many studies on the effects of various colors of light on biological process, but the limited data in the literature indicate that varying light spectra may have significant effects. Although it is not clear whether rodents can perceive colors (Gouras and Ekesten, 2004), work suggesting that rodents cannot recognize red light and distinguish it from darkness dates to 1969 (Spalding *et al*., 1969a). Most nonprimate mammals typically have only two types of cone pigments (Jacobs *et al*., 2001, 2004). In mice, as for other nocturnal animals, one cone variety serves the ultraviolet spectrum (the short-wave subfamily) and the other resembles the human green-yellow region of the visible spectrum (the middle wavelength subfamily) (Gouras and Ekesten, 2004). The advantage of ultraviolet vision is in a broadening of the visual spectrum, increased sensitivity to all light (including that which is reflected), and added forms of visual contrast (Gouras and Ekesten, 2004). The spectral sensitivities of the two corresponding cone types in the mouse retina show maxima at 350–365 nm and 509–512 nm as determined by electroretinography and behavioral testing (Sun *et al*., 1997; Gouras and Ekesten, 2004; Jacobs *et al*., 2004). Similar maxima have been observed in gerbils, gophers and rats (Sun *et al*., 1997). The furthest toward the short wavelength end of the visual spectrum perceived by humans is 410–420 nm (Gouras and Ekesten, 2004). The differential perception of light by wavelength has an effect by extension to various biological processes, including activity, reproduction, growth and hormonal function. The voluntary wheel-running activity of mice is strongly influenced by differently colored lights (Spalding *et al*., 1969a, 1969b). Wavelength of light may affect body weight and organ weights in mice (Saltarelli and Coppola, 1979), fecal output from rats in behavioral paradigms (Williams, 1971) and, possibly, sexual development (Piacsek and Hautzinger, 1974). Young female rats under a 14:10 light:dark cycle matured at a significantly slower rate when the day-period light consisted of dim red (80 lux, peak wavelength = 655 nm) as opposed to brighter blue (400 lux, peak wavelength = 445 nm) light (Piacsek and Hautzinger, 1974). Interestingly, this effect was reversed when continuous lighting at each wavelength was provided, and was interpreted to be due to the biologically fatiguing effects of continuous light exposure (Piacsek and Hautzinger, 1974). The spectrum of ambient lighting has been shown to influence the growth, gonad weight and incidence of dental caries in hamsters (Sharon *et al*., 1971). Blue or white light has been shown to provide protection against bilirubin toxicity, and stunt the growth of infant rats (Heller *et al*., 1969; Ballowitz, 1971). Different colors of light have been shown to alter sexual cycles in ferrets (Bissonnette, 1933). Ott (1964) reported that guppies kept under blue fluorescent light for 9 hours daily ceased all reproduction, while guppies under pink fluorescent light produced normal numbers of young but the sex ratio was altered to 80 percent females and 20 percent males. Chinchillas housed and bred outdoors with natural light produced equal numbers of male and female offspring. When the breeders were moved indoors and housed under incandescent lights they produced mainly male offspring, and when the lights were changed to blue lights virtually all the young produced were female (Mulder, 1971). Housing mice under pink light caused unthrifty young, shorter breeding lives, smaller litters and shorter life than seen with natural or white light (Ott, 1964). Without additional information regarding the spectral characteristics of the pink, natural or white light it is difficult to interpret these findings, except to conclude that pink lighting hues should be avoided in the animal research facility. Different colored lights influence human biological rhythms (Morita and Tokura, 1998). Stephan (1963) lists several effects of various wavelength lights on animals. These include a tranquilizing effect by blue violet light, stimulation of hormones by red orange light, slight stimulation of hormones by green light, increase in thyroid function by red light, vagatonizing and prolactin-activating effect of cold red (short-waved) light, and respiratory activation, stimulation of endocrine organs and metabolism, depression of blood pressure and increase in erythrocyte count by ultraviolet light (depending on wavelength) (Stephan, 1963). A concern in research, specifically related to behavioral phenotyping, extends to the validity of studies historically done on nocturnal animals, but manipulated during periods of light and often when the animals are aroused from rest. As research in this regard is considered with greater sensitivity, there will likely be increasing emphasis on reverse light-cycle studies, including the quality of light (if any) providing during the dark cycle, as well as the introduction of technological accommodations enabling human night vision.

By design, lighting should be diffused throughout the animal room and be of sufficient intensity to permit husbandry activities and animal observation. In some cases, vertical orientation of light fixtures on walls, especially in cubicles, may be more beneficial and appropriate in terms of providing uniformity of illumination than traditional overhead lighting. Individual animal housing rooms should be designed with dual-control

levels for general illumination and task lighting. The general requirement for the former is 30 foot-candles (~323 lux) measured 1 meter from the floor and controlled by an automatic timer for the former (ILAR, 1996) with manual boosting by override mechanism to 60–70 foot-candles for personnel working in the room. The position of the cage relative to the source of light will have effects on health and biological processes. Ocular lesions are most common in rats housed on the top shelf of racks (Rao, 1991). When a room is illuminated by ceiling lights, animals on the top rows are exposed to higher light intensities than those housed elsewhere. This stratification of illumination may reverberate to myriad biological processes, such as the rapidity of sexual maturity or development of retinal degeneration. Where important, the incidence of eye lesions can be reduced by management interventions, such as rotating cages on the rack every 2 weeks and decreasing the light intensity to less than 50 ft-candles at 5 ft above the floor (Rao, 1991). The photoperiod should be controlled using electric or mechanical timers. The optimal photoperiod for research animals has not been determined, but 12:12 light:dark cycles has traditionally been used. In some cases, in particular for breeding rodents, 14 hours of light and 10 hours of darkness has been found useful. A potential complication emerges where timing of electronic security and environmental control systems converge; this requires careful consideration and harmonization of light-cycling with staff access. This may be especially important where security access is adjusted for daylight-saving time but the photoperiod is not shifted in concert.

Since rodents and other nocturnal mammals cannot effectively discern red light from darkness and humans can visually adjust to red light, filter materials absorbing blue and green light but allowing peak transmission of red wavelengths are preferred in animal research facilities for door-viewing window-tinting and fluorescent bulbs, sleeves or tube guards enabling dark-period illumination. The Ruscolux 26 (Rosco Laboratories, Stamford, CT) red light filter, or equivalent, is fabricated from polyester and polycarbonate, highly durable and heat-resistant, and is the recommended prototype. It allows 12 percent light transmission, including 80 percent of all light in the 660- to 700-nm red wavelength, while blocking 95 percent or more of light transmission at any wavelength below 540 nm (Figure 7-3). Glass-tinting films, such as those used for automobile or storefront windows, can be used, but should be shown to obstruct appropriate light wavelengths. A commercial window-tinting film product (Vivarium Red Film, Aegis Applied Films, Norcross, GA) blocking light wavelengths below 650 nm and adhering easily and reliably to door-viewing windows is used at Emory University (W. D. Thompson, 2005, personal communication). Another approach to allowing people to see and work in the dark cycle in mouse housing areas is the use of sodium lamps (McLennan and Taylor-Jeffs, 2004). Sodium light is bichromatic, with both wavelengths being at the margin of murine vision but in the human visual field, providing a light level that is comfortable to humans but sufficiently dull to permit nocturnal behavior in mice. Sodium lighting has been used to observe the nocturnal behavior of various strains of mice for more than one-and-a-half years. The mice were invariably awake and alert during the nocturnal/sodium-light phase (McLennan and Taylor-Jeffs, 2004).

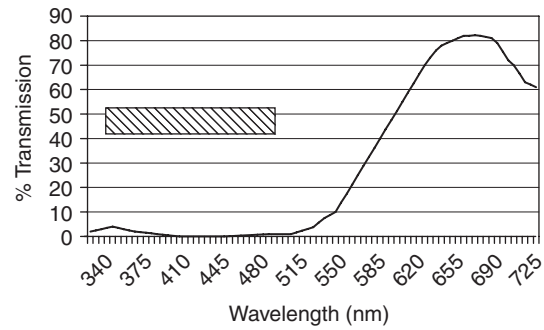

Fig. 7-3 Approximate Ruscolux 26 filter light wavelength transmission (nm) as extrapolated from Rosco Laboratories, Stamford, CT. Approximate range of mouse visual acuity shown by striped bar and adapted from Gouras and Ekesten (2004) and Jacobs *et al*. (2004).
Figure compliments of Michael J. Huerkamp.

Owing to the importance of photoperiod consistency and regularity, and its impact on virtually every biological response, monitoring of light and dark cycling is critical. Undetected lighting failures occur most commonly in the form of continuous illumination from failed timers. Lights remain on after operating hours when staffing is non-existent to negligible, and direct observation of the environment may be rare. As such, lighting malfunctions, particularly illumination during the scheduled dark period, may go on for extended periods of time. Additionally, lights may also be manually activated during the dark cycle, particularly by research personnel at night. Light emitted from biosafety cabinets inadvertently left on into the evening from daytime use or specifically used at night may also confound photoperiodicity. For this reason, the cycling of the photoperiod should be nominally monitored using electrical current sensors for each lighting level in each room, and most optimally in combination with photocell sensors. The former will monitor when electrical lights are powered, and the latter will monitor extraneous room lighting during the dark cycle – such as from lamps, biosafety cabinets and the like. This technology, supported by a microprocessor security control and recording system, facilitates the detection of lighting malfunction due to mechanical failure, identifies situations of manual lighting at night, and also provides leads to the culpable. A particular threat to alter dark-period cycling that should be accounted is the graduate student/research technician who is characterized by innate, preternatural peak activity and productivity during crepuscular and dark periods (the so-called “night person”).

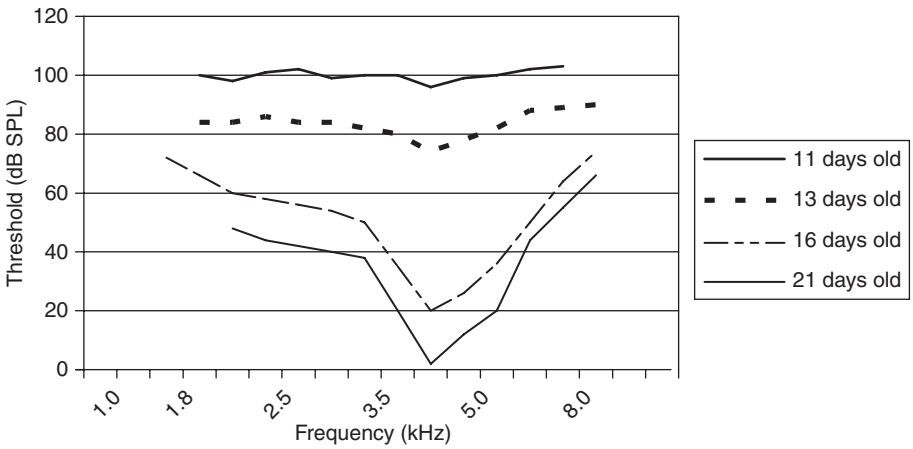

Fig. 7-4 Development of hearing perception in rat pups as demonstrated by auditory brainstem response thresholds.
Adapted from Alberts (1988).

IV. NOISE

Noise is present in many environments, and remains one of the main environmental problems of modern society (Ouis, 2001; Ising and Kruppa, 2004; Rabat, 2007). There are numerous sources of noise in research animal facilities. In the evaluation of noise, consideration must be given to both qualities of sound pressure level (decibels) and frequency (wavelength). Noise originates from ventilation systems, personnel and equipment movement, vocalization and activity of animals, husbandry and cleaning procedures, from light fixtures and computer terminals, and from the operation of equipment. It has recently been shown that vacuum cleaners produce noise that is audible to mice (Naff *et al*., 2007). An important and sometimes overlooked factor is the noise from adjacent construction or renovation/expansion projects, and the need to buffer the noise impact for at-risk populations (Fernandes and File, 1993). Patterns of sound exposure can also have adverse effects on animals. Excessive or loud, sudden impact noise, such as that from fire alarms, overhead speakers, radios, loud conversations, equipment collisions, barking dogs, squealing pigs, or monkeys vocalizing and shaking cages, can have a negative effect on rodents and rabbits (Clough, 1982). Noise exposure can induce or accelerate hearing loss in mice, confounding studies involving learning or hearing acuity (Crawley, 2000).

The noise levels in animal facilities in frequencies discernible by humans may vary between <30 dB and 102 dB throughout the day (Pfaff, 1974; Peterson, 1980). Milligan *et al*. (1993) monitored sound in animal facilities in both low- and high-frequency ranges, and found that during the work day sound levels commonly reached values of 80–95 dB in the low-frequency range (0.01–12.5 kHz) and 50–75 dB in the high-frequency range (12.5–70 kHz). There are broad auditory and non-auditory systemic effects of noise exposure that include changes in neuroendocrine and cardiovascular function, the sleep–wake cycle, seizure susceptibility, reproduction and development, and immune function; alterations in the toxicologic properties of certain agents; and an array of behavioral changes (Zondek and Tamari, 1964; Geber *et al*., 1966; Peterson, 1980; Nayfield and Besch, 1981; Ivanovich *et al*., 1985; Turner *et al*., 2005, 2007; Rabat, 2007). Additionally, there are strain, species and age differences in hearing, and these differences affect an animals' response to sound (Alberts, 1988; Zheng *et al*., 1999; Turner *et al*., 2005). Rat pups, for example, don't show significant hearing sensitivity or discrimination until after 2 weeks of age (Figure 7-4). As an example of both age and genotype influences upon hearing, Zheng and colleagues (1999) assessed 60 murine genotypes for auditory brainstem response thresholds, and found a number to be hearing impaired. Strains of 129, A, DBA/2 and NOD background become deaf at an early age (<13 weeks), while others, such as C57BL/6, BALB/c and DBA/1, develop late onset, age-associated, progressive presbycusis beginning by 8–40 weeks of age (Mikaelian *et al*., 1974; Zheng *et al*., 1999; Crawley, 2000) (Figure 7-5). The response is also affected by the noise intensity level, duration and predictability, and other characteristics of the sound, and partly by animal history and exposure context. Man has the lowest upper cut-off hearing frequency of all species so far examined, and therefore sounds that are inaudible to a human are perceptible and may be stressful to rodents (Clough, 1982) or other species. As an example, humans hear in the range of about 20–20,000 Hz (Warfield, 1973); rats in the range of 100–70,000 Hz (Warfield, 1973) and mice in the range of 500–120,000P Hz with greatest sensitivity in the 10- to 24-kHz range (Gamble, 1982; Zheng *et al*., 1999). Mice have been demonstrated to have bimodal sensitivity, with a second range of acute perception at 30–70 kHz (Gamble, 1982). At 16-kHz wavelength, CBA/J and CBA/CaJ strains, widely considered to be normal controls for hearing research, can sense sound pressures as low as 14–16 dB (Zheng *et al*., 1999). Likewise, at 16 kHz, the mean sensitivity (± 1 standard deviation) for 430 individual mice representing 60 strains was 18 ± 4 dB. Although ostensibly not comparable in a straightforward manner, from an

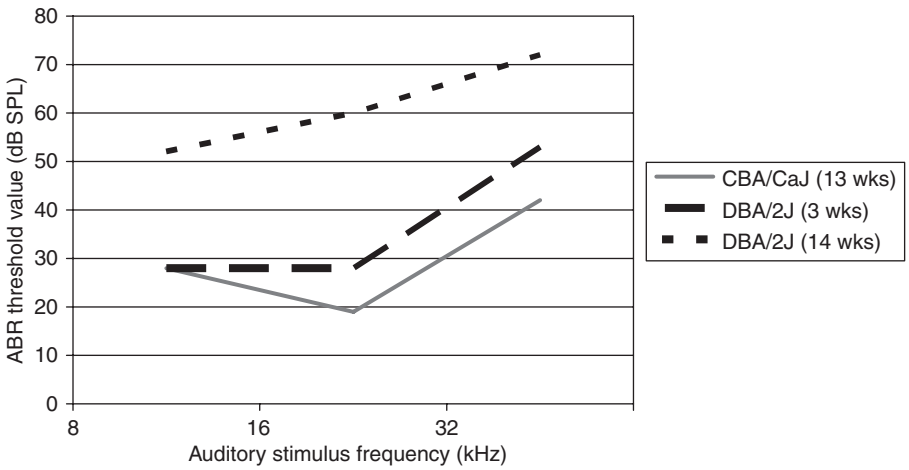

Fig. 7-5 Hearing acuity in mice as shown by auditory brainstem response (ABR) thresholds and demonstrating range of normal hearing sensitivity (CBA/CaJ) as compared to a strain with early onset deafness (DBA/2J).
Adapted from Zheng *et al.* (1999).

anthropomorphic perspective this is the decibel level of the ticking of a watch or a whisper at the 2,000-Hz frequency audible to humans (Peterson, 1980). Mice commonly emit ultrasonic vocalizations of frequencies exceeding 80 kHz and sometimes up to 100 kHz or more (Liu *et al.*, 2003; Gourbal *et al.*, 2004). Decibel levels that exceed the usual background noise in animal facilities cause various degrees of destruction of sensory hairs and supporting cells of several animal species (Fletcher, 1976). Similar to man, rats experience mechanical damage at 160 dB, pain at about 140 dB, and signs of inner ear damage after prolonged exposures to about 100 dB (Anthony, 1962). Cats, chinchillas, monkeys and guinea pigs are reported to be more sensitive to acoustical trauma than are humans (Peterson, 1980). Chinchillas, in particular, have been demonstrated to be susceptible to damage from low-frequency noise (Peterson, 1980). Guinea pigs are most susceptible to damage of the organ of Corti as newborns (Falk *et al.*, 1974), mice shortly before weaning (Sanders and Hirsch, 1976), and hamsters between 27 and 55 days of age (Bock and Sanders, 1977). A concern has been raised that ambient ultrasound may be common in animal facilities; its effect on laboratory animals should be investigated, and guidelines on acceptable levels be formulated (Sales *et al.*, 1988). Given the perceptions of rodents in the range of 500 Hz to 120 kHz, ultrasound in the animal facility may be of concern. Ultrasound emitted from fluorescent lights, in particular, may be confounding in the animal research facility. Commercially-available bat detectors have been reported as useful in identifying ultrasonic noises and their sources in areas where animals are housed or studied (Jennings *et al.*, 1998).

Noise stress may reduce fertility of rodents (Zakem and Alliston, 1974; Fletcher, 1976), and loud noise disrupts the estrus cycle in rats (Gamble, 1976), affects components of blood (including plasma lipids, corticosterone, total cholesterol, serum glutamic oxaloacetic transaminase (SGOT), serum glutamic pyruvic transaminase (SGPT), and triglyceride levels) (Geber *et al.*, 1966; Friedman *et al.*, 1967; Prabhakaran *et al.*, 1988), and causes myocardial damage (Paparelli *et al.*, 1995; Gesi *et al.*, 2002a, 2002b) which exhibits gender differences (Soldani *et al.*, 1997). Rats exposed to 90-dB noise for 15 minutes a day exhibit increased microvascular leakiness (Baldwin and Bell, 2007). Noise stress results in increased adrenal weights in rats and rabbits, pathological changes in the adrenal cortex (Soldani *et al.*, 1999; Gesi *et al.*, 2001; Frenzelli *et al.*, 2004), increased circulating corticosterone levels (Soldani *et al.*, 1999; Gesi *et al.*, 2001), and reduced spleen and thymus weights in rabbits (Nayfield and Besch, 1981). Noise also affects components of the immune system, as evidenced by a significant increase in thymus weight and cell count, a significant decrease in antibody titer and spleen weight and cell count, a reduction in the migration of pre-thymic stem cells to thymus, suppression of macrophage function, and time-dependent suppression and enhancement of splenic lymphocyte proliferation in response to mitogen stimulation and splenic natural killer cell function following noise stress (Bomberger and Haar, 1992; Spehner *et al.*, 1996; Van Raaij *et al.*, 1996; Archana and Namasivayam, 1999, 2000). It impairs wound healing (McCarthy *et al.*, 1992; Wysocki, 1996) and affects the adrenals and their function, with acute noise stress resulting in increase in dopamine, noradrenaline, adrenaline and their metabolites, and a polarization and an increased numerical density of noradrenaline and adrenaline granules in the cells; while chronic noise stress results in significantly increased noradrenaline levels and significantly decreased adrenaline levels (Gesi *et al.*, 2001, 2002c), increased durations of exploring, grooming and resting behaviors (Krebs *et al.*, 1996), reduced food intake (Nayfield and Besch, 1981), and cardiovascular effects including the significant increase in systolic blood pressure and increase in pulse pressure and vasoconstriction (Peterson, 1980; Wright *et al.*, 1981; Gao and Zhang, 1992; Baudrie *et al.*, 2001). Additionally, noise stress has been shown to impair prefrontal cortical cognitive function in monkeys (Arnsten and Goldman-Rakic, 1998). Rhesus monkeys exposed to wide-band frequency noise of 100- to 110-dB

intensity had significantly impaired delayed-response performance to visual discrimination testing. There are sex, strain and age differences in the response to noise stress (Glowa and Hansen, 1994; Blaszezyk and Tajchert, 1996; Baudrie *et al*., 2001; Pryce *et al*., 2001; Faraday, 2002; Maslova *et al*., 2002). The banging of cages in an animal room can cause a 100–200 percent increase in plasma corticosterone in rats, which persists for 2–4 hours (Barrett and Stockham, 1963). It has been shown that the noise of oxygen rushing into a hyperbaric chamber contributed to the incidence of convulsions of rats being treated with hyperbaric oxygen (Boyle and Villanueva, 1976). Exposure of pregnant rats to an 85- to 90-dB fire alarm bell results in alteration of immune function in the offspring (Sobrian *et al*., 1997). Rats appear to adapt to chronic noise stress (Armario *et al*., 1984, 1985).

The idea of playing background music as white noise, or the use of other white-noise sources to mask sudden noises in a facility, is one that has been around for quite some time. Music has been shown to reduce the effects of noise stress (Nunez *et al*., 2002). A source of white noise in an animal facility may be beneficial, and there is evidence supporting the use of quiet music during non-human animals' active periods (Patterson-Kane and Farnworth, 2006). White noise appears to render macaques calmer during blood collection (Kawakami *et al*., 2002), and to reduce the amount and intensity of barking in laboratory-housed dogs (Kilcullen-Steiner and Mitchell, 2001). The use of white noise must be undertaken with an awareness of the risks to animal welfare and research. The introduction of music in the laboratory environment may have unforeseen negative effects (Patterson-Kane and Farnworth, 2006). Music may act as a stressor. Random noise events (aircraft noises), as well as classical music, have been shown to have a marked negative effect on the fearfulness of laying hens compared with normal barn noises (Campo *et al*., 2005). Loud radio may create stress leading to negative responses, such as the salivary cortisol response of marmosets to radio music at 70–80 dB (Pines *et al*., 2004) and blood glucose increase in dogs to 80-dB sound (Treptow, 1966). Captive chimpanzees react differently to various types and genres of music, with the varying reactions depending on both the sex of the subject and the type of social behavior examined (Videan *et al*., 2007). Additionally, animal studies have shown exposure to a broadband noise stimulus (including a wide range of frequencies) reduces the specificity of auditory cortex neurons, resulting in improved responses to noise at the expense of responses to frequency-specific pure tones (Chang and Merzenich, 2003; Zhang *et al*., 2003). These results suggest that rearing animals in constant white noise which masks background noise may have negative consequences for normal development of the auditory system by effectively masking the normal input to the ear from vocalizations and other sources (Turner *et al*., 2005). Low-level environmental sounds may mask communication signals between animals, perhaps explaining some of the adverse effects of noise (Cohen and Weinstein, 1981).

Certain species of research animals, such as dogs, pigs, monkeys, etc., are capable of generating significant sound-pressure levels. It has been reported that a single German shepherd dog can produce sound-pressure levels approaching 120 dB at 2,000 Hz and lower, with peak energy centered in the 500-Hz energy band (Sierens *et al*., 1977; Peterson, 1980). Noise in animal rooms generated by the animals in the room has been reported to be as high as 110 dB in dog rooms and about 80 dB in pig rooms (Sierens, 1976). Monkey cage-rattling has been identified as a greater source of noise than vocalization, and as having pressure levels exceeding 80 dB and peaking at 95 dB within a range of 250–8,000 Hz (Peterson, 1980). Human activity is a major source of noise variability in the animal research facility (Milligan *et al*., 1993), although noise generated by humans tends to be of low frequency and generally less than 2 kHz in frequency (Peterson, 1980). Taken in total, however, the risks created by noise reverberate to programmatic and engineering considerations, and impact design in the form of sound-attenuation strategies, room size and dimension limitations (i.e., number of racks or scientists using each room), and the relationship of rodent housing areas to those areas with non-rodents. Frequent human traffic in and out of breeding colonies, for example, has been shown to disrupt GI development in rats (Wilson and Baldwin, 1998). Buffering research subjects from the variability introduced by humans into the environment has generated an emerging interest in the development of isolation suites and systems that merge science with housing to enable behavioral phenotyping, telemetric physiologic measurements, etc., with minimal or detached human involvement (Bohannon, 2002b).

When considering noise and its sources in animal facilities, it is important to bear in mind noise generated by ventilation systems for ventilated caging systems. The supply and/or exhaust blowers units produce macro-environmental and micro-environmental noise. The volume and frequency of the noise generated is dependent on the system type and the number of units per holding room. In an investigation of three commercially available ventilated caging systems, all three were shown to produce macro- and micro-environmental noise significantly greater than room background noise. Macro-environmental noise ranged between 74 and 80 dB, while micro-environmental noise ranged between 79 and 89 dB (Perkins and Lipman, 1996). Sound frequencies above 16 kHz were not tested. Another group reported no detection of ultrasonic frequencies produced by a ventilated caging system (Clough *et al*., 1995). To fully understand the potential effect of noise generated by ventilated caging systems on rodents, these units need to be evaluated for sounds over the complete hearing range of rodents. Sound levels for multiple ventilated caging systems in a room are determined by a logarithmic equation. In a room containing four units generating 80 dB each, the room noise level would be 86 dB – which is above the 8-hour exposure level established by the American Conference of Governmental Industrial Hygienists (Lipman, 1999).

From a design perspective, the goal for animal housing and study areas should be for ambient noise to be kept at approximately 55 dB and sound attenuation should be considered, especially where frequencies of 10–100 kHz may be encountered. Standard doors are particularly susceptible to noise leaks. The use of soundproof doors or double doors with an air lock may be desirable. Noise transmits through walls. The denser the walls, the less noise transmission; therefore, walls of plasterboard mounted on studs transmit more noise than do concrete masonry unit walls. Split stud walls transmit less noise that normal stud walls. Hollow walls may be filled with materials such as sand or Styrofoam beads to reduce sound transmission. Flooring materials also affect sound levels. Seamless sheet vinyl floors are quieter than epoxy floors or floors of other dense, sound-reflective materials. Air conditioning ducts may be direct sources, or transmitters, of noise. The use of proper, isolated anchoring of the duct work, fiberglass duct lining, smooth transitions in duct cross-section, and outlet baffling can greatly reduce noise in individual rooms and inter-room cross-talk (Peterson, 1980). Increased security and isolation for rodent breeding colonies, facilitated by design, should be considered. In consideration of the floor plan, rodent housing and study areas should be isolated and insulated from noisy animals (pigs, dogs, non-human primates) and loud activities (e.g., cage-wash, intercom systems). While critical in terms of human life safety, fire alarms can be a source of sudden, distressful noise and flashing strobe lights. Optimally, fire alarms for the animal research facility should emit low noise (70- to 100-dB) and low frequency (<1,000-Hz) chime alerts without strobe lights. If necessary, it is recommended that strobe lights be installed in hallways, providing such is consistent with the local fire code and ordinances. Both the Honeywell Model XLS-757-7A-CS (Honeywell International, Inc., Morristown, NJ) and Silentone Alarm (Arrowmight Biosciences, Hereford, UK) meet these criteria. In the prevention and management of noise in the animal research facility, as influenced by design and construction, consultation with a qualified acoustician should be considered.

Because noise can have profound and wide-ranging effects on animals, Willott (2007) has recommended that measurements of sound-pressure levels in animal facilities should be made and provided to researchers. The current authors agree with this recommendation. These measurements should be made both in animal housing areas and procedure rooms, and should include sounds associated with ventilated caging and laminar flow workstations. The measurements should be made by a well-trained individual using high-quality sound measuring equipment, preferably capable of measuring sound frequencies from 10 to 100,000 Hz. Additionally, measurements should be made within octave bands to characterize potential influences of high, middle or low frequencies (Willott, 2007). These data would provide investigators with an empirical description of the acoustic environment in which the animals are housed and/or raised, and would help identify potential acoustic problems within a facility.

V. INFRASOUND AND VIBRATION

Infrasound is sound of a frequency range below the level of normal human hearing (i.e., less than 20 Hz). Infrasound has a relatively long wavelength with a low material absorption rate, and thus has the ability to travel vast distances. This sound is very non-directional in its propagation, and therefore has the effect of enveloping the individual without any discernable localized source. Infrasound has an intrinsically mysterious effect, as it is usually felt and not heard (Davies, 2000).

> When male volunteers were exposed to simulated industrial infrasound of 5 and 10 Hz and levels of 100 and 135 dB for 15 minutes, feelings of fatigue, apathy, and depression, pressure in the ears, loss of concentration, drowsiness, and vibration of internal organs were reported. In addition, effects were found in the central nervous system, the cardiovascular system, and the respiratory system. Synchronization phenomena were enhanced in the left hemisphere. Visual motor responses to stimuli were prolonged, and the strength of the effect was reduced. Heart rate was increased during the initial minutes of exposure. Depression of the encephalic hemodynamics with decreased venous flow from the skull cavity was observed. Heart muscle contraction strength was reduced. Respiration rate was significantly reduced after the first minute of exposure.
> (Boom Car Noise, 2001; http://www.lowertheboom.org/trice/index.htm)

The following incident serves to demonstrate that exposure of animals to infrasound can result in negative effects. Two groups of rats in two consecutive studies were observed to steadily lose weight over a 2-week period after being moved into the same animal room (Motzel *et al.*, 1996). Normally, these rats would be expected to lose some weight immediately after the move and then begin gaining weight. A third group of rats was placed in the room, and they suffered a similar persistent weight loss. Exhaustive testing ruled out possible infectious, environmental and husbandry etiologies. Coincidental to the incidents of weight loss, there were mechanical changes ongoing in the building. An outside consultant was brought in to measure vibration and sound levels, including ultrasound and infrasound. Floor vibration was found to be very low, but sound-pressure levels were higher in the affected room than in adjacent rooms; the sound was of very low frequency, in the range of 1–10 Hz. It was discovered that the air handler serving the room was misaligned. Once the misalignment was corrected, the sound pressure in the room was reduced and animals placed in the room gained weight normally – including the animals that had previously lost weight in the room (Motzel *et al.*, 1996).

Sources of infrasound include ventilating systems, electric generating plants, engines in submarines, compressors, cooling towers, and overhead motorway bridges (Buros, 1973; Nishimura *et al.*, 1987). Infrasound has been shown to produce deleterious effects in people (Johnson, 1974; Takeda, 1979, 1980; Matsumoto *et al.*, 1980; Nagai, 1984). Experimental exposure of laboratory animals to infrasound has been reported to cause effects. Exposure of rats to infrasound for 3 hours per day for 5–40 days resulted in the development of

irreversible alterations in the liver, characterized by ischemic areas with morphologic and histochemical changes in hepatocytes (Nekhoroshev and Glinchikov, 1992). Similar exposure of guinea pigs and rats to infrasound resulted in changes in the myocardium, including spasms of the main coronary vessels which led to the development of ischemia resulting in destruction of myocardiocytes (Alekseev *et al*., 1983).

There is a condition in man know as vibroacoustic disease (VAD), which is a whole-body, systemic pathology, characterized by the abnormal proliferation of extracellular matrices, and caused by excessive exposure to low-frequency noise (LFN) (noise $\leq$ 500 Hz) of large pressure amplitude (LPA) ($\geq$ 90 dB) and whole-body vibration (Branco and Alves-Pereira, 2004). While noise of this frequency is not infrasound by definition, it is sound at the low end of the frequency spectrum. VAD has been observed in LFN-exposed professionals, such as aircraft technicians, commercial and military pilots and cabin crew members, ship machinists, restaurant workers and disk-jockeys, and has also been seen in several groups exposed to environmental LFN (Branco and Alves-Pereira, 2004). LFN exposure causes thickening of cardiovascular structures with pericardial thickening with no inflammatory process, this in the absence of diastolic dysfunction being the hallmark of VAD. There are mental disturbances associated with VAD. These include depression, increased irritability and aggressiveness, a tendency to isolation, and decreased cognitive skills (Gomes *et al*., 1999; Branco and Alves-Pereira, 2004). LFN has been shown to be genotoxic, causing an increased frequency of sister chromatid exchanges, and an increased incidence of malignancies has been reported in LAF-exposed individuals (Silva *et al*., 1999; Branco and Alves-Pereira, 2004). VAD patients have an increased prevalence of skin and respiratory infections and significant elevation in the number of circulating CD8+ and CD4+ T lymphocytes when compared with the control population (Castro *et al*., 1999).

Animal studies have shown a number of effects resulting from LFN exposure similar to those seen in VAD patients. When Wistar Rats were exposed to LFN for 8 hours a day, 5 days a week for a total 1,236 hours of exposure, there were significant degenerative changes in the ciliated tracheal epithelium (De Sousa Pereira *et al*., 1999). Similar results were reported for rats exposed to LFN *in utero* or postnatally (Oliveira *et al*., 2001). The respiratory lesions caused by long-term exposure are irreversible, while those caused by shorter periods of exposure are reversible (Castelo Branco *et al*., 2003). In addition to the tracheal changes LFN also causes changes in deep lung tissue, including focal interstitial fibrosis and increase of alveolar type II pneumocytes (Grande *et al*., 1999). Further studies have shown LFN exposure of rats to result in thickened alveolar walls, thickened walls of pulmonary vessels, and a reduction in the number of macrophages in the lung (Branco *et al*., 2004). Long-term exposure of mice to LFN results in immunological perturbations, as exhibited by a decrease in splenic T cells, both helper (CD4+) and cytotoxic (CD8+) lymphocytes, and IgM + B cells (Aguas *et al*., 1999). LFN exposure also interferes with resistance to bacterial infection in rats (Oliveira *et al*., 1999). Finally, as in man, exposure of animals to LFN leads to increased levels of sister chromatid exchange (Silva *et al*., 2002).

There are a number of anecdotal accounts of the negative impact of vibration on research animals. The effects are said to include reduction of breeding efficiency in breeding colonies, reduction in food intake and weight gain, and behavioral modifications. However, there are very few controlled studies on the effects of chronic whole-body vibration at small acceleration to be found in the literature. Large-acceleration vibration can have negative impact. Mice subjected to a simulated severe earthquake and five aftershocks had a very significant increase in the rates of cleft palate and fetal resorption (Montenegro *et al*., 1995). In early work for the space program rats subjected to vibration amplitudes of 4.6 cm at 283 cycles/minute for 15 to 30 minutes a day for 21 days exhibited severe effects on body weight, food consumption, leukocyte counts and organ weights (Sackler and Weltman, 1966). Exposure of pregnant rats to vibration with an acceleration of 10 m/s^2 at a frequency of 8 Hz resulted in significantly decreased uterine blood flow and decrease of corticosterone, progesterone and prostaglandin E2 levels (Ohsu *et al*., 1994; Nakamura *et al*., 1996).

VI. WATER

Water, whether used for drinking purposes or as the constituent medium of an aquatic environment, is a variable that can profoundly affect research. To minimize adverse impact upon experiments, water used in the animal resources program must be fresh, potable and uncontaminated. Water entering an animal research facility will typically be supplied from a local domestic source (although sometimes from wells), meeting general standards appropriate for human consumption. This water, however, may still be subject to considerable variation, depending upon a number of factors, including geographic locale, the proximity to industrial, urban or agricultural settings, and municipal treatment approaches. As such, water may be contaminated to some degree by pesticides, herbicides, heavy metals, PCBs, nitrogen fertilizers, micro-organisms, radionuclides, drugs and pharmaceuticals, volatile organic compounds, and other impurities or noxious waste (Lipman and Perkins, 2002). Most groundwater in the United States is also considered to be "hard," containing high levels of calcium, magnesium and/or iron that, when used for cleaning or distributed for drinking purposes, may predispose to mineral scale within pipes (including automated watering systems), on surfaces or within sipper tubes. The most reliable epidemiologic data linking certain "as delivered" drinking water impurities with disease are derived from humans. Lead is probably the best known heavy metal with well-characterized toxic effects in humans, especially fetuses and children. It is, as well, an established teratogen and reproductive intoxicant for rodents

(Ronis *et al*, 1996; Zheng *et al*., 1996; Apostoli *et al*., 1998). Outbreaks of cryptosporidiosis, a chlorine-resistant protozoan, associated with municipal drinking water have been well-documented in the disease surveillance literature (Kramer *et al*., 1996). Even human chemical poisonings from sodium hydroxide accidentally dumped in drinking water at a treatment plant have occurred (Lee *et al*., 2002). Pesticides and fertilizers found in groundwater have been demonstrated to cause cytogenetic splenocyte damage in mice and rats (Kligerman *et al*., 1993). Although some species of fish and amphibians may tolerate low levels of chlorine or chloramines, many are sensitive to even the low concentrations found in municipal drinking water and will die from the effects of exposure (Kaplan and Glaczenski, 1965; Astrofsky *et al*., 2002; O'Rourke and Schultz, 2002). Therefore, it is critical routinely to purify water supplied from community sources as it enters the animal research facility and before delivery for animal consumption or use in aquatic environments.

It should be appreciated, however, that under certain circumstances drinking-water treatment interventions intended for laboratory animals can introduce research variability that must be anticipated and addressed. Hyperchlorination (12–15 ppm) or acidification (pH 2–2.5) of tap or purified drinking water, either singularly or in combination, have been advocated for over 40 years as means of suppression of the endogenous, opportunistic microflora of research rodents, and particularly Gram-negative bacteria (McPherson, 1963; Woodward, 1963; Hoag *et al*., 1965; Les, 1968). Acidified water, in particular, has a proven record as being especially useful in the maintenance of mutant immunologically impaired rodents (Eaton *et al*., 1975). Even these seemingly well-intentioned interventions to prevent opportunistic infections, however, can have confounding research effects under certain conditions. Hyperchlorinated drinking water has subtle immunosuppressive effects (Fidler, 1977; Exon *et al*., 1987), and chlorinated municipal drinking water may have genotoxic properties (Park *et al*., 2000). Chlorine may also react with residual organic material in the water, resulting in a number of byproducts with potential pathologic effect – most importantly, mutagenicity and carcinogenicity (Holme *et al*., 1999; Komulainen, 2004). Chlorine reacting with various trihalomethane substances produces chloroform – a cause of liver tumors in mice and female rats, and renal tumors in male mice and rats (Komulainen, 2004). The production of chlorinated furanones (CHFs), such as 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5 H)-furanone (MX), has been shown to cause thyroid and hepatic cancers in rats (Komulainen, 2004). If the pre-treated water contains bromide, chlorinated drinking water may also contain brominated byproducts, some of which (bromodichloromethane, bromoform) have been shown to be carcinogenic in laboratory animals (Komulainen, 2004). Free chlorine in drinking water may also evaporate over a few days, ultimately resulting in consumption of waxing and waning amounts over the experimental lifetime of an animal with possible biological effect. In water bottles, chlorine has been shown to dissipate in 3 days from 12 ppm to undetectable levels (McPherson, 1963). While acidification offers a more stable alternative to chlorine (Hall *et al*., 1980), acidified water may leach substances from water-bottle stoppers (Kennedy and Beal, 1991) and be damaging to surfaces in the facility that are not suitably resistant. In mice, acidification has been associated with pH-dependent alterations in weight gain and water consumption (Hall *et al*., 1980). Water acidification has also been shown to reduce splenic mass, resulting in decreased host phagocytic capability (Hermann *et al*., 1982). Even water softening, often employed to extract minerals from water and prevent scaling of the plumbing system, may be a source of sodium of concentrations that may be undesirable in drinking water under certain experimental or health circumstances. Finally, autoclaved glass water bottles, long considered to be inert, can be a source of silicon crystal contamination of drinking water (Lohmiller and Lipman, 1998). More ominously, there is emerging evidence that thermoplastics, such as those used to fabricate drinking bottles, may leach endocrine disruptor byproducts, such as bisphenol A, into water and the animal environment (Howdeshell *et al*., 2003).

In general, the carcinogenic potential of the broad array of chemicals and byproducts in drinking water is not well understood, indubitably complex, and only of nascent definition (Komulainen, 2004). However, the risk is of sufficient significance that the only logical course of action is to remove any impurities. Optimally, water entering the animal research facility should undergo sediment and carbon filtration, water softening and additional purification prior to distribution for animal consumption. This water, if used for aquatic species, may require additional treatment to replenish certain salts and trace minerals vital to health, provide buffering capacity, and by and large simulate a natural aquatic environment (Allee *et al*., 1940; Astrofsky *et al*., 2002).

VII. CONCLUSIONS

The animal research facility, through the provision of consistent and wholesome environmental conditions as free as possible of confounding variability, is the foundation upon which valid research can be done. Research animals respond to many factors or changes in their environment. These responses may affect experimental results. The greater the understanding of the effects that environmental elements can have on biological processes, the better the variables can be controlled – or at least the better experimental results can be discussed in light of them. A constant, reproducible environment (to within prescribed limits) is desirable to minimize the physiological variations associated with environmental changes; however, the effective control of all environmental variables at all times is a difficult goal. Nonetheless, all reasonable attempts should be made to control those environmental factors most likely to

interfere with the work in progress. Records should be kept of environmental variables relevant to the research programs in the facility, and there should be the capability to document significant deviations from allowed ranges of variation. Planned significant environmental changes should not be made without prior consultation with the investigators, to ensure that minimal impact occurs to research programs. A cardinal rule of laboratory animal science and medicine is always to keep in mind that procedures carried out in health and husbandry programs may have significant effects on research results.

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Chapter 8

Cost

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I. COST OVERVIEW

Cost inevitably becomes a driving factor in any development program. Animal research facilities are no exception; with building cost approaching $700.00 per square foot, cost must be considered during each phase of program development, construction and operation of the facility. In reality, a "cookie cutter" laboratory does not exist. While labs have similar and predictable characteristics based on their intended use, seldom are they repeated frequently enough to allow the development of reliable parametric pricing tools. Consequently, each facility must be priced individually based on its unique components, quantities and markets. To avoid potentially devastating surprises in cost is to employ proactive cost management, consistently, as the program develops. The cost of including this is far less that the cost of excluding it. Cost management has saved many programs from an ill-fated cancellation due to lack of funding.

As in any building, there are multiple cost drivers in an animal research facility. Some are fundamental and obvious, while others are more discreet and indirect. Regardless, each impacts the price an investor pays to develop the program into an operating facility. To simply ignore any would be foolish and shortsighted.

Market conditions affect the cost from beginning to end. All contracted services – architectural, engineering, construction management, programming and so on – will vary, based on supply and demand. If professional firms providing these services are busy and operating at or near capacity, it will generally cost more to procure them services than when they are slow or need work. Moreover, in boom times, when most firms have resources fully engaged, the chance of receiving sub-par work goes up because skilled people simply are not available in the numbers needed.

The location of the facility is a driver of cost. Often the location is dictated, and the site simply must be dealt with. This does not diminish its impact or make it any less of a cost determinant. The purchase or lease cost of the property is an obvious item. Beyond this are other considerations. A site must be adapted to the building, and site adaptation cost increases with the complexity of change that is needed for construction to begin. This change may include clearing and grubbing, clean-up, demolition, remediation of existing conditions, removal of unsuitable soil, addition of fill material and protection of surrounding space.

The proximity of the site to needed utilities is a factor. It must be remembered that, in addition to traditional utilities such as electricity, water, sanitary sewer and fuel, animal research facilities require other services, such as network connections, medical gas services, disposal of potentially hazardous material, and a constant supply of support products to sustain housed animals. The cost of all these vary geographically, but in each case tend to increase with the distance of delivery.

Finally, location will likely impact permitting cost. Facilities of this type carry a stigma of public concern that requires permits and studies far in excess of that necessary to build "just another classroom." There are environmental impact studies, wind-current modeling, noise analysis, and other possible requirements imposed by special interest groups that must be satisfied. Sometimes, it is cost-effective to build on a different site rather than appease the insatiable demands of a hostile public.

Before discussing other costs and cost drivers, we need to set forth a common understanding for terms that will be used. As the following terms are applied in this chapter, each should be considered in the context of the accompanying definition.

Capital cost: the expense of acquiring, substantially improving, expanding, changing the functional use of or replacing a building or building system is considered its capital cost. This is non-recurring and represents the initial outlay of funds and or other resources to acquire the facility. The terms "building" and "facility" are used interchangeably. In addition to the physical structure, they include the components and systems within the physical structure and on the grounds that support the facility's operation.

Lifecycle cost (LCC): lifecycle cost is the total economic impact of ownership, which includes the cost to purchase (capital cost), the cost of operation over the period of ownership, and the credit for any salvage value at the end of the ownership term. LCC is expressed in present-value or annual-value terms. Cost of operation includes expenditures for utilities, maintenance, repair, replacement, and other expenses required to keep the facility in operation during the selected term.

Flexibility cost: research is constantly evolving and, consequently, a facility supporting research must be capable of adapting to future needs and changing programs. There is a premium associated with making a facility adaptable to multiple uses over only meeting a narrowly defined program. This premium is defined as flexibility cost, and can be analyzed either from a capital-cost approach or a lifecycle-cost perspective.

Value engineering (VE): Value engineering is the utilization of engineering fundamentals such as the application science and mathematics to identify and study design alternatives that have the potential to increase value of the project from the owner's point of view.

Assignable to gross efficiency (E a/g): The efficiency of a building is defined as the ratio of useable program space to the total space required to deliver the program. It may relate to the entire building, or might be used to describe a sub-component or individual program. For example, if a particular laboratory has, by actual measurement, 1,000 square feet of floor space on which laboratory operations such as research, processing and documentation take place but that particular laboratory uses a 1,250 square-foot section of floor plate when considering corridor space, chase space, equipment space and other support space required for the lab, then the E a/g for the lab is 1,000/1,250, or 80 percent. As is clear from the example, when equating a facility to its cost per square foot, it is important to know the basis.

II. COST

Capital cost is probably the easiest of the program costs to identify, and is loosely equated to the cost of construction. Although animal research facilities are very specialized, they share some similarities with other buildings and building programs. For example, its structural component is usually very conventional. It has exterior weatherproofing and esthetic components. Inside, some of its interior space is sized and partitioned to meet the programmed needs of the user, while additional interior space is sized and partitioned to facilitate use of the programmed space or support the needs of the user, such as bathrooms, break rooms and corridors. Additionally, rooms are provided to enclose supporting equipment such as transformers, heating and air conditioning equipment, laboratory gas equipment, laboratory exhaust equipment, animal ventilation equipment and so on.

UniFormat, published by the Construction Specification Institute, is a grouping tool commonly accepted by the industry to categorize building elements into identifiable systems, the sum of which define the facility. Since it is "systems" oriented, it makes finding the cost of a specific system in a cost model easy, as well as providing a good place holder to ensure no system is overlooked when establishing the model. Basic building systems in UniFormat are summarized as follows:

A10 Foundations
A20 Basement Construction
B10 Superstructure
B20 Exterior Enclosure
B30 Roofing
C10 Interior Construction
C20 Stairs
C30 Interior Finishes
D10 Conveying Systems (Elevators, Escalators, etc.)
D20 Plumbing
D30 HVAC (Heating, Ventilating, Air Conditioning)

D40 Fire Protection Systems
D50 Electrical Systems
E10 Equipment (Fixed equipment other than the above)
E20 Furnishings
F10 Special Construction
G10 Site Preparation
G20 Site Improvements
G30 Site Civil/Mechanical Utilities
G40 Site Electrical Utilities
Z10 General Requirements

UniFormat is relatively new, and most contractors prefer to use CSI's MasterFormat when preparing actual bids because that is the format around which the specifications are organized and it has long been the standard for the construction industry. The cost model is usually converted to the MasterFormat when based on 100 percent construction documents to facilitate reconciliation with the general contractor.

UniFormat will be used to frame our identification of major cost drivers important to consider in the development of an animal research facility building program. Before looking at the categories individually and delving into detail, it is important to realize that the sum of the HVAC (Mechanical), Plumbing and Electrical systems (MEP) is perhaps the most potent of all cost drivers. MEP cost as high as $278.00 per square foot has been encountered. When compared to a traditional Class A office building having a component cost of only $37.00 per square foot for its MEP work, the impact of these systems can be appreciated. It should be borne in mind that this only contemplates capital cost. Operating cost, which tracks proportionately, must be added to this to obtain the life-cycle cost.

Taking the categories individually gives an understanding of what makes animal research facilities unique, and the characteristics that have the greatest impact on cost.

Foundations generally account for 1–3 percent of the construction cost, and are affected very little by the fact the facility is designed for animal research. Foundations cost is driven more by the soil conditions beneath the building and the work required to develop a stable platform to anchor the building. Therefore, site selection has a big effect on design and resulting cost of the foundation.

Basement construction does not substantially change the cost of the project unless it requires a large amount of rock to be moved or perhaps needs substantial dewatering to construct. Occasionally, designers prefer placing multiple levels below grade, requiring deep excavations. Depth and protection of adjacent property sometime dictate the use of sheet pile shoring and/or a soil tie-back system. Either of these could be considered a "red flag" for a cost premium, and suggest the space might be constructed above ground for less cost.

The above-ground framework of the building, which incorporates columns, elevated slabs and shear walls, is categorized as the superstructure. Depending on the design, this could be fabricated with structural steel, poured-in-place concrete, pre-cast concrete, or a combination of these. Except for two exceptions noted in the paragraphs below, buildings constructed for animal research usually do not carry a premium in the structural cost, even though the design load on lab floors is heavier than that for common office slabs. The choice to use concrete versus steel for the basic structure will affect the cost, just as it does in any building. This is predominately based on geography and contractor expertise in the area. Both should be researched before committing to a design because, depending on local conditions, either approach could offer noticeable cost savings over the other.

Research facilities include unusually large amounts of mechanical, electrical and lab support infrastructure run through the building. This, combined with the desire to have generous ceiling heights in work areas, usually produces floor-to-floor heights that are greater than the 12-foot standard. Superstructure cost goes up as the floor-to-floor height increases above the norm.

Progressive collapse is a failure phenomenon in which the collapse of an elevated slab onto the slab below causes it to collapse also – leading ultimately to failure of the entire structure. Traditionally, buildings are not designed to resist progressive collapse, as the failure of an entire slab is not something to be contemplated. However, with animal research so closely tied to biomedical engineering, the facility is a potential target for terrorist attack. Protecting against this threat has become one of the biggest factors in the cost escalation of these facilities, and represents as much as 10 percent of the total construction cost. Many of these facilities are now designed to resist progressive collapse. Constructing to these specifications can increase the cost of the superstructure by as much as 40 percent.

The exterior enclosure is also driven to a large extent by security considerations. Sometimes it is required to resist the blast of an explosion or the force of a ram. Obviously, glass is one of the more vulnerable materials. Glazing and framing that meets blast-resistant standards can double the cost over conventional material. Wall thickness may be increased by 50 percent to meet blast-proof criteria, driving the unit cost up proportionately.

Esthetics, as with any other building, will have a big influence on the cost of the enclosure. Aside from special materials and methods selected solely for security reasons, the shape of the building and the material used to "skin" the facility determine to a large degree the cost of the enclosure. Curves, arcs and the number of directional changes along the exterior face can add significantly to the cost. Moreover, the material and its availability in the local market have a major effect. Esthetic choices can add $30s to the cost per square foot of the facility.

Animal facilities are generally roofed with conventional methods comparable to other buildings. Consequently, roof prices are consistent with those for other buildings. Unusual, though, is the number of roof penetrations and the amount of

equipment found on the roof. The roof system should be easy to seal at penetrations and be resistant to damage caused by foot traffic; otherwise, maintenance cost will increase.

Interior construction includes partitions, doors and other fixed construction within the confines of the exterior walls. For the most part animal facilities do not have an inherent premium for interior construction, but there are a few notable exceptions. For instance, housing large animals requires very substantial (strong) construction. Partitions used in these areas are usually masonry blocks or, in some cases, poured concrete. Masonry walls cost approximately 50 percent more than drywall, while concrete walls are twice the cost of drywall.

BSL3 and BSL4 protocols dictate that certain pressure relationships be maintained between rooms. This leads to specialized sealing at partitions, far in excess of what is normal. Labor cost to accomplish this can be quite high, particularly in BSL4 space. Although the cost is high, the work is usually not required in a large percentage of the building; however, in buildings that have large areas of BSL3 and BSL4 space this cost will become significant. Not only does the partition cost go up, but also the finish. Special coatings will be addressed in the discussion on finishes. Lab doors tend to cost more than common doors because many have view-lights in them and often special hardware is required. Additionally, door cost is influenced by the same two factors as affect walls – animal resistance and BSL requirements. Naturally, doors that are designed to facilitate and prevent the movement of large animals are special items and cost considerably more. Usually, an effective air seal can be achieved across a door by the inclusion of relatively inexpensive gasket material between the door and its frame. However, caution should be used when considering agricultural, BSL4 or other highly secure space, and doors with marine-style pneumatic expandable gaskets are sometimes called for. One such door can cost upwards of $20,000!

Stair requirements, resulting construction and cost are no different in animal facilities, and will predictably run at about $1 per square foot.

Interior finishes of walls, floors and ceilings are generally functions of the space utilization. Latex wall paint is commonly used as wall finish in offices and medical space. As a rule of thumb, this runs at approximately $0.70 per square foot installed. Using this as a basis, higher-performance glazed coatings for lab rooms may add $0.30 per square foot. More specialized coatings are sometimes required to resist damage, or for exceptional sealing qualities in BLS3 and BSL4 space. Epoxy-based coatings meet these criteria, but installed cost of epoxy can be as much a four times higher than that of latex paint.

Floor finishes for non-specialized lab areas and offices are usually a sheet vinyl material, and cost in the range of $6 per square foot. Wet areas, rooms subjected to frequent washdowns and vivarium rooms are likely to have a resinous-based floor. Resinous floors cost in the range of $13–14 per square foot, or twice as much as a conventional floor covering.

By far the most popular ceiling treatment is acoustical lay-in ceiling tile, which is used extensively in all areas of the building except BLS3, BSL4 and animal housing. Installed cost of acoustical tile is about $3 per square foot. In other areas where tighter sealing and greater durability is required, drywall ceiling with epoxy paint is preferred. That system costs almost three times that of acoustical tile, i.e. $9 per square foot.

Based on the total size of the building, wall finishes typically account for $4 of the cost per square foot, floor finishes for $9 and ceiling finishes for $3 dollars.

Conveying systems, such as passenger and freight elevators, can be budgeted at $3 per square foot for a multi-storey building. Animal facilities often require specialized lift equipment, particularly when dealing with large animals. While not a major item, in the overall sense it should not be overlooked. An industrial-style hoist costs about $6,000.

Plumbing costs in these facilities are completely disproportionate to those of any other building, and vary greatly from lab to lab. Plumbing cost will generally run from between $30 and $60 dollars per square foot. Ironically, for a given size the traditional plumbing cost are less than in a typical office building. Occupancy density in the facility is less; therefore, less plumbing is needed for bathrooms, break rooms, water fountains, janitors' closets and the supporting systems, such as hot and cold water pipes, drain waste and vent pipe, and the storm drainage system. All this costs in the order of $3 per square foot, and is obviously not the driver of the laboratory plumbing cost. The drivers are the specialized systems and equipment dictated by procedures carried out in the facility. A big contributor is equipment to treat the specialized wastes that are byproducts of the operation. Large animal facilities often equate to large and expensive plumbing systems. The following list illustrates some of the additional work that adds to the plumbing cost. While almost no labs include all of these, most labs include a large percentage.

1. Domestic water hot and cold to all lab tables and lab outlets
2. Domestic water hot and cold to all lab tables and lab outlets isolated in specified containment areas
3. Tempered water to emergency showers and eye-wash fixtures
4. Tempered water to emergency showers and eye-wash fixtures isolated in specified containment areas
5. Bio-waste waste and vent piping and filters
6. Bio-waste waste and vent piping and filters in containment conduit
7. Chemical waste piping
8. Acid waste piping
9. Chemical shower piping
10. Natural-gas piping (low and medium pressure)
11. Carbon dioxide piping
12. Compressed air piping
13. Vacuum pipe

14. Vacuum pipe isolated in specified containment areas (BSL3)
15. De-ionized water pipe
16. Breathing air piping
17. Breathing air piping isolated in specified containment areas (BSL4)
18. Nitrogen gas piping
19. Liquid nitrogen cryogenic piping
20. Oxygen piping system
21. Lab waste pipe (BSL2)
22. Lab vent pipe (BSL2)
23. Lab waste pipe (BSL3)
24. Lab vent pipe (BSL3)
25. Lab vacuum exhaust pipe
26. Animal water-system pipe
27. Animal water-system pipe (BSL3 (In Animal Lab Rooms))
28. Plumbing utility hook-up of all process equipment
29. Floor drains in wash-down areas, at all sterilizers, at autoclaves and as required by other process equipment
30. Floor drains suitable for bio-waste in animal holding areas
31. Floor drains isolated in specified containment areas (BSL4)
32. Flushing rim floor drains and controls
33. Trap primers for all floor drains
34. Water heaters for individual hot water systems
35. Pressure-reducing stations
36. Backflow prevention stations for each water system
37. Air compressor, receiver and equipment for laboratory compressed air
38. Air compressor, receiver and equipment for breathing air
39. Vacuum pump
40. Water softener
41. Reverse osmosis water treatment system
42. Chemical showers and equipment
43. Bio-waste treatment tanks and equipment
44. Laboratory gas storage equipment and dispensing manifolds
45. Carbon dioxide storage and handling equipment
46. Liquid nitrogen storage and handling equipment
47. Liquid nitrogen generation equipment
48. HEPA filters for bio-waste tank vents
49. HEPA filters in bio-waste vent pipe (BSL-4)
50. HEPA filters in carbon dioxide pipe penetration (BSL-4)
51. HEPA filters in oxygen pipe penetration (BSL-4)
52. HEPA filters in vacuum pipe penetration (BSL-4)
53. Tissue digester and disposal equipment
54. Booster pumping package for water system
55. Lab waste neutralization system
56. Hose stations and mixing valves for wash-down (BSL-2 and 3)
57. Stainless-steel laboratory sinks and trim
58. Stainless-steel laboratory cup sinks and trim
59. Foot-operated pedal valves for all laboratory fixtures
60. Insect traps in lavatory drains
61. Lift stations for all gravity drainage systems below the site sewer elevation.

The extent to which these systems are required will determine the plumbing cost.

Without question, the most significant system in a modern animal research facility is the mechanical heating, ventilating and air conditioning system. It rises to the top in almost any category – size, cost, importance, etc. Usually this system will account for one-fourth of the building cost, running to as much as $130 per square foot in some of the more expensive markets.

The influence of the mechanical system on the project goes beyond this. Animal research requires mechanical systems of much larger capacity than conventional systems, for reasons we will later address. Larger systems require more space for the equipment, ductwork and pipe. More space equates to more cost; in the order of $200 per square foot. Larger systems also require more power to operate – hence, larger electrical systems and more cost. This snowball effect is sometime difficult to follow. But make no mistake; the mechanical system is key to understanding where many of the extraordinary costs in an animal facility stem from.

Why are these systems so large? At the risk of oversimplification, consider first the fact that, for reasons beyond the scope of this discussion, ventilation rates in laboratories are usually in the order of 10 air changes per hour. This means that every 6 minutes the total volume of air inside the building is taken out and the building filled with new – not unlike the operation of a bellows. Work is required to empty the bellows, and work is required to fill the bellows. Sometimes referred to as the ventilation rate, 10 times per hour is easily double the ventilation rate of other workspace. Following this logic down the line, the size of the mechanical system is directly proportional to the amount of air it must move. Size determines cost.

Looking one layer deeper reveals another factor that further leverages the effect the ventilation rate has on driving cost up. In other buildings, ventilation rates are achieved with recirculated air. Old air returns from a space to an air conditioning unit, where it is reconditioned (cleaned and tempered) and then circulated back into the space. The air is reused – recirculated. In animal facilities, this is not the case. Air is used only once. This means that for each ventilation cycle, fresh air from outside the building is used to fill the space and the air removed from the space is eliminated from the building. In theory, this necessitates two air distribution systems as opposed to one – and two cost more than one.

"Once-through air" creates more expense. First the air from outside must be cleaned (filtered), then altered to the correct moisture level (humidified or dehumidified) and finally adjusted to the correct temperature (heated or cooled). To have the capability to do this through all seasons of the year, the equipment must have much greater capacity than would

be needed to perform the same work on recirculated air. Additionally, safety and environmental concerns require that the air removed from the building be clean before it is released. Depending on the level of risk, the cost of the exhaust filtration system can easily exceed that of the supply filtration system.

The mention of filtration in conjunction with research always leads to the HEPA (high-efficiency particulate arrestor). Because of the HEPA's ability to do just that – capture very small particles – it is an effective barrier to the objectionable and sometimes deadly micro-particles that are the essence of research in these facilities. HEPA filters are installed in virtually every air path that communicates with a BSL3, BSL4 or vivarium space. In most instances, there will be multiple areas of containment within similarly classified space – for example, a BSL4 floor may have 10 different lab suites, and each suite is considered a separate containment area. Therefore, rather than a few large filter banks serving a large common space, many small filter banks are required to isolate not only the sum of the space but also each piece of defined containment from the other. Depending on the material and accessories, a typical HEPA filter bank will cost in the range of $25,000!

Precise environmental control in each room required by lab protocol is a further factor affecting price. The rooms are controlled not only for temperature and humidity, but also for pressure. Control zones, while sometimes larger than a single room, are small when compared to more conventional space – usually half the size. Current technology uses air valves, sometimes referred to as variable air volume (VAV) boxes, to regulate the amount of air put into the space, as well as the amount of air taken from the space. The controlling device will maintain a differential between the air supplied and the air removed to create the desired pressure relationship. The exhaust flow is a function of the air supplied to the room, as well as any requirement for removal of localized procedural air, such as hoods, canopies and snorkels. The supply air is a function of maintaining the room's desired temperature, as well as the meeting the required offset between supply and exhaust. Supply air is cooler than the room; therefore, when the room temperature begins to rise more air is allowed to enter the room to overcome the rise and then maintain the desired temperature. Conversely, when the room temperature drops below the desired temperature, the supply air is reduced as much as possible while still meeting the minimum requirements for ventilation. If the reduction in cool air does not allow the room to warm to the desired temperature, the supply air is then heated to a higher temperature by a heating coil located in the supply-air ductwork downstream of the air valve. All of this is sequenced by the zone-controlling device, which is capable of sensing and assimilating the necessary information, making logical decisions based on this information and then controlling the aforementioned hardware to maintain the desired conditions – which can also be changed if so desired. If all this sounds complicated, it is – and expensive. The controls and hardware alone for a small room (225 square feet) will cost $13,000.

Finally, after the mechanical system has been sized large enough to simply meet the minimum requirements, its *actual* size often doubled to allow for safety factors and redundancy.

Water sprinkler systems are used most frequently for fire protection. Density and piping is usually comparable to that of other buildings; however, due to the unusual amount of coordination required to install the work, prices are usually 50 percent higher. These can go much higher when pre-action controls or gas-extinguishing systems are added.

Electrical work, as previously stated, is driven in scope and cost by other requirements within the building. The electrical service and power distribution is abnormally large because of the unusually large mechanical system and its redundancy. The electrical gear and feeder wire to distribute this can cost as much as $20 per square foot – more than the total electrical cost in most buildings.

Interior lightning and its associated controls vary substantially. Fixtures are more specialized depending on the procedures they support and the environments they inhabit. Light-intensity level is often variable in animal rooms, and controlled automatically to mimic daily cycles with programmable frequencies. Lighting premiums overall will double the cost of traditional lighting systems and wind up accounting for $7–14 of the final square-foot cost.

The same can be said for convenience power outlets. Far more are utilized per square foot in research areas than is the case in office areas. Additionally, fewer outlets are wired on the same circuit. The result is more material and more cost. Convenience power contributes between $2 and $4 to the unit cost – again, a minimum of twice that in an office building.

Both the lighting and power costs spike in BSL3 and BSL4 space when positive air seals are required. Electrically, the seal is accomplished using solid-cast device boxes and conductor conduits filled with epoxy sealant at all barrier penetrations and wall outlets. Each box and accompanying sealant can cost as much as £100, depending on the specifications – 50 times the cost of a standard wall box!

Security in research facilities is always a concern, but the cost of providing it increases exponentially as the potential danger from exposure goes up or protection from terrorism is emphasized. Security can be grouped into two categories; surveillance and notification, and access control. Each adds about $2.50 to the cost per square foot. The access control number can be much higher when automatic bollards and anti-ramming roadway wedges are used to stop vehicle access.

Data cabling is usually extensive to support the research and monitoring requirements. Although considerably more than in other buildings, it is usually less than $2 per square foot.

Fire alarm, grounding and lightning protection systems tend to cost pretty much the same as in convention buildings – perhaps slightly more.

Unique requirements for closed circuit television, integrated audio/visual units, remote teaching, video recording, video conferencing and other media-driven systems have not been

included in the previous discussion. When required, each must be added to the cost, and the cost of each will vary extensively based on the scope of work.

Emergency or stand-by power is always required to some degree in these facilities. The minimum is usually dictated by life safety codes; however, the total is usually more a function of the user's adaptability to a power outage and the dependability of the utility power source. To substantially back-up the building with a diesel-powered source such that experiments can be reasonably maintained, animal needs can be met and minimal staffing can continue will add $10 per square foot to the cost.

Fixed equipment costs must always be handled on an individual basis, as they are completely program-driven. The value can range from almost nothing to more than $30 per square foot. The following are examples of the equipment that falls into this category:

1. Animal cages
2. Bedding material dispenser
3. Food handling equipment
4. Bedding material disposal equipment
5. Necropsy equipment
6. X-ray and other advanced imaging equipment
7. Environmental rooms
   - 7.1 Cold storage rooms
   - 7.2 Tropical storage rooms
   - 7.3 Aquatic storage rooms
8. Self-contained laboratory hoods and research chambers
9. Sterilizers
10. Autoclaves
11. Ice machines
12. Flash freezers
13. Cage-washing equipment
14. Glass-washing equipment
15. Cell-sorting equipment
16. Irradiation equipment
17. Incubators
18. Centrifuges
19. Spectron microscopes
20. Ovens
21. Incinerators.

Furnishings are usually limited to the laboratory furniture and casework, window treatments, and miscellaneous non-fixed items such as entry mats, pedestrian ropes and writing surfaces. Obviously, the major contributor to cost in this category is lab equipment. While its cost varies with the materials and finishes selected, it will usually fall between $5 and $15 per square foot.

The last category to mention is that of special construction. Although this may not be used, it is important to be aware of the fact that thus far the discussion has been based on generic construction. Any unique features, such as monumental stairs, fountains, atriums, etc., will increase the final cost.

Mentioned in several places above is the term *operating cost*. As stated in the definitions, this is added to the capital cost along with the maintenance cost less the salvage value over a specified period of time to determine the lifecycle cost.

Maintenance costs include preventive work, routine work and repair work. Costs may be accrued over a period for the following:

1. Roof repairs
2. Window washing
3. Painting
4. Caulking
5. Grounds keeping
6. Janitorial cleaning and housekeeping
7. Waste handling and disposal
8. Periodic adjustment and repair of hardware
9. Periodic certification inspections
10. Chemical treatment of water systems
11. Specialized operating personnel, such as boiler operators, chiller operators, electricians
12. Scheduled filter inspection and replacement
13. Scheduled lubrication and belt replacement
14. Replacement of failed electronic components
15. Replacement of luminaries
16. Exercise of stand-by power systems.

Many more items can be added to the list. However, the significance is to understand that maintenance is a core cost of the facility, and cannot be ignored if informed decisions are to be made regarding cost.

The same holds true for operating cost. Operating cost is the cost of utilities consumed by the facility as a function of its operation. A reliable rule of thumb is, the bigger the system, the more it costs to operate.

III. VALUE MANAGEMENT

With an understanding of the major factors that contribute to the cost of a facility, true value management can be realized when that knowledge is used in the application of formal value engineering (VE). Value engineering should never be confused with simple "cost cutting" or "scope reduction," as has happened in some circles. Rather, value engineering is an organized process to achieve goals and to better manage limited budgets. The process identifies opportunities to remove unnecessary cost while assuring that quality, reliability, performance and other factors determined as being important meet or exceed the customer's expectations.

The process employs teams, carefully assembled with multidisciplinary representation, directed by an impartial facilitator trained in the practice of value engineering. The team may consist of people who are involved in the design and development of the project, of technical experts that have not been involved with the project, or a combination of the two. Varied

representation broadens the perspective and tasks each discipline with a "value" responsibility, thereby increasing the probability of producing significant, meaningful results.

The objective of any VE study is to improve the value of that being studied where value is the most cost-effective way to reliably accomplish a function that will meet the quality and availability expectations of the customer. Too often decisions are based on just one criterion, such as cost, quality or reliability. This leads to less than optimum results. A decision that improves quality but increases the cost to a point where the product is no longer marketable is just as unacceptable as one that reduces cost at the expense of quality or performance. It is also important to avoid confusing cost with value. Added material, labor or overhead increases *cost*, but not necessarily *value*. Value is diminished if added cost does not improve the ability to perform the necessary functions.

Performance, delivery, cost, importance and usefulness all provide a measure of value and, considered collectively, are synonymous with *worth*. If worth is equated to monetary terms and divided by the actual price paid to obtain it, the result is a number known as the *value index*, Vi = W/C. This index allows value to be quantified; a larger index indicates a greater value. Mathematically and practically, this is realized by increasing worth without changing cost, decreasing cost without changing worth, or doing both.

A *job plan* leads the team through the process of achieving this. Its phases are:

1. Information and function analysis
2. Creative
3. Evaluation
4. Development
5. Presentation/report
6. Implementation.

Following these steps in sequence and avoiding the temptation to jump ahead, trying to solve a problem before it is thoroughly understood, is essential to the effectiveness of the VE process.

The first step involves developing a common understanding among all team members about the project. Included are understanding the customer's needs, requirements, goals and funding limitations; understanding the proposed design; understanding anticipated costs to deliver as proposed; and understanding unique construction or scheduling challenges associated with delivering as proposed. Meticulous planning and preparation are required to disseminate this information to the team succinctly and efficiently.

Any facility, whether for animal research or another purpose, exists to satisfy certain needs, and does so through the functions it provides. Once the team has a common understanding of the project, it names these functions, determines the cost of providing each, and establishes their dependent relationships. This is at the heart of VE methodology, and is known as functional analysis. It will identify focus points within the project as presently proposed that are ripe for value improvement.

The creative phase generates as many ideas as possible to improve the project in the areas chosen for focus. Brainstorming techniques are used and all ideas generated, regardless of merit, are recorded for later evaluation. Postponing evaluation and any critique establishes an environment in which creativity thrives.

Only after the team's creative energy has been thoroughly tapped does evaluation begin. In this phase, each idea is evaluated against program value objectives, which are criteria important to the customer. The ideas that score highest in this evaluation are used for further development. Others are discarded, while some may be retained for later consideration.

In the development phase, the ideas chosen as having the most promise are technically improved into workable concepts and specific proposals that provide alternatives to the project as presently proposed. These alternatives, the team believes, will increase value to the customer when incorporated into the project. Each proposal must enumerate the advantages and disadvantages of implementing the proposal, the estimated cost or saving of its implementation, and specifics of what is required to bring about its implementation.

Finally, the proposals are explained to both the customer and the design team in an oral presentation and written draft. This provides a forum in which all aspects, including emotional concerns, can be communicated. After the presentation, and with feedback from all parties, the report is finalized and given to the customer. It is then the prerogative of the customer and the design professionals to incorporate the ideas into the final design as they so desire.

IV. CONCLUSION

All too often the cost of a facility is set after the plans and specifications are finished, and a contractor using reactive estimating techniques to quantify components then values each, using units of material, equipment and labor, and offers a price. Cost management, on the other hand is proactive in nature and tracks anticipated cost from conception to construction, with adjustments along the way to change the budget when necessary or change the design when constrained by budget, and utilizes the discipline of value management to make good decisions in the best interest of all stakeholders.

A final caution before closing: cost management, cost containment and cost control can be severely compromised if the plans and specifications are loosely prepared or the program is ill-defined, thus relying on the change-order process to get the project successfully finished. Change orders are never cost efficient and, while some will be necessary, minimizing their need should be give high priority before any documents are issued for pricing.

Section II

Design Concepts and Considerations

Chapter 9

Circulation

Pierre A. Conti and Jack R. Hessler

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I. INTRODUCTION

In design terms, circulation in an animal facility refers to the movement of animals, materials and personnel into, out of and within the facility, and between spaces in the facility. Other terms that apply include flow (Ruys, 1991), traffic patterns and circulation patterns. Ruys divided the animal facility into four zones based on the level of potential contamination: public zone, transitional zone, pathogen-free zone and contaminated/dirty zone. As described by Ruys, the public zone includes areas of unrestricted access where special protective clothing is not required. These areas include the receiving dock, public corridors, administrative spaces and, possibly, unrestricted laboratories and storage rooms. The transitional zone is an interface between the public zone and the pathogen-free zone, consisting of dressing rooms, air showers, air locks and other decontamination or protective features. The pathogen-free zone may include some facility corridors, animal rooms, barrier facilities, the clean side of cage-washing and the clean-cage holding room. The contaminated/dirty zone consists of quarantine and biocontainment facilities, the necropsy lab,

soiled cage-wash and waste holding. These zones should be considered when designing circulation systems for the animal facility. In this regard, thought should be given to flow cycles for all elements that move through the facility, and the potential impact on protection of the animals and personnel from contamination. The following list summarizes traffic into, within and out of the animal facility:

- people – animal-care personnel, administrative personnel, veterinary staff, animal health technicians, research technicians, investigators, maintenance personnel, vendors and visitors;
- animals – animals being received, animals being shipped out, animal transport within the facility and animals transported to laboratories outside the animal facility;
- cages and equipment – clean cages and equipment, soiled cages and equipment, cages and equipment being transport into and out of the animal facility;
- supplies – feed and bedding receipt, storage and dispensing; sanitation chemical receipt and dispensing;
- laundry – receipt of clean laundry, shipping out of soiled laundry;
- waste – disposal of liquid waste and solid waste, including soiled bedding, shipping containers and general trash.

Access and egress circulation patterns for all the above-listed people and items, along with circulation patterns within the facility, need to be carefully thought out early in the planning process with a goal of facilitating efficiency, reducing cross-contamination and preventing unnecessary exposure of personnel to animals and animal waste products.

Facility criteria such as size (footprint), physical location, animal and people demographics, and facility purpose are the primary factors that drive circulation decisions. In addition, site criteria such as geographic location, degree of isolation, environmental restrictions, security requirements and site services all impact on how personnel move into and out of the animal facility, how animals are received, how trash is removed, and how and where materials are received and stored.

In the conceptual design stage of the project, bubble diagrams may be used to identify functional adjacencies and then link them with the appropriate traffic patterns (see Figure 9-1).

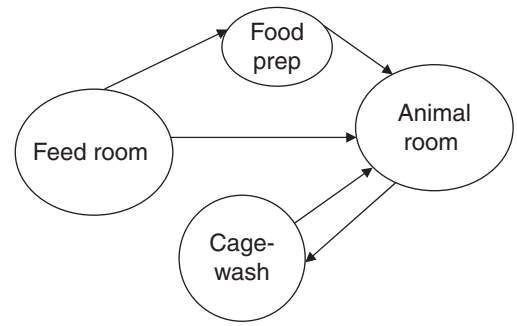

Fig. 9-1 Example of how bubble diagrams can be used to illustrate flow patterns.

II. MOVEMENT OF MATERIALS

During the design phase the circulation of materials should be addressed, including receipt, staging site(s), distribution and disposal for each type of material involving a significant volume.

A. Feed

Feed is generally delivered at the animal facility dock in 40-pound bags stacked on pallets that are stored in the feed storage room. From there it is handled a bag at a time and dispensed into cages either in the clean side of the cage-wash or in animal rooms. For this reason, the best location for feed storage is near the clean side of the cage-wash area. If the cage-wash area is not central to the animal rooms, secondary feed storage rooms near the animal rooms may also be required. Feed should be stored in temperature-controlled rooms to maintain the nutrient quality of the feed over the reported shelf-life. Some research programs and animal species require the feeding of fresh fruits and vegetables that need refrigerated storage to maintain food quality and freshness. Research programs that use synthetic diets may also require that these be kept refrigerated. Refrigerated food storage may be located within or adjacent to the primary feed room, or adjacent to the area where the refrigerated food will be used. Some institutions will house all of their feed products in a central refrigerated feed room. Other programs and species require that foods be prepared before feeding. This is usually done in a specific food preparation area that may be adjacent to the feed room or located in the area where the animals requiring the special food preparation are housed. This is a common practice in non-human primate housing areas, where fresh food needs to be portioned into servings and where special food treats are prepared as part of the animal enrichment program. In large institutions with multiple animal facilities, there may be one central feed storage room that will distribute feed to satellite feed rooms. The central feed storage will be located close to the receiving dock, and the satellite feed rooms will be located near animal housing or cage-wash areas in remote sites or separate buildings. Alternatively, feed may be delivered by the vendor to each animal housing site.

B. Bedding

In medium- to large-sized facilities, bedding may be stored separately from feed. In smaller facilities, feed and bedding may be stored in the same room unless the feed is stored in a refrigerated room. Contact bedding is typically delivered in 40-pound bags that are stored on pallets in the bedding storage

room. The bags are usually handled one at a time as the bedding is placed into animal caging or dumped into automated or semi-automated bedding dispensing machines. Either way, the best location for bedding storage is as close to the clean side of the cage-wash as possible, preferably in a room with two doors, one from the corridor and one leading directly into the clean side of the cage-wash. Soiled contact bedding is dumped from cages on the soiled side of the cage-wash, where it is either disposed of into the sanitary sewage system or dumped into trash bags and carted by hand to a dumpster, typically located at the dock. In some situations, a room off of the soiled side of cage-wash may be required for storing the soiled bedding until it can be carted off at the end of the day or after-hours. In very large facilities, especially those utilizing robotic cage-handling, contact bedding is stored in bulk storage containers in or near the dock. The containerized bedding is then delivered to the clean side of the cage-wash area via various types of automated conveyance systems (see Chapter 31). Similar conveyance systems are used to transport the soiled bedding from the soiled side of the cage-wash to disposal containers outside the animal facility.

Non-contact bedding, usually provided in sheets or rolls, is delivered to the animal housing area from the central bedding storage room. This type of bedding is usually changed within the animal room, bagged, and taken to the trash collection area or dock for disposal. Special handling may be required for non-contact bedding coming from rooms where infectious or hazardous materials may be present. This might require packaging in special containers, holding these containers in a specific hazardous-waste holding area, and then delivering the containers to a designated trash dock for pick-up and disposal. Bedding, both contact and non-contact, from studies where radioactive materials are used will require special handling, storage and disposal.

C. Caging

Caging circulates through several functional areas of a facility. Cage movement and location are dependent on a number of factors, three of which apply to all caging: (1) they serve as a primary enclosure for an animal; (2) they must be cleaned in accordance with regulatory or institutional dictates; (3) when not in use, they must be stored. The method of cleaning, the type of cage, and the purpose and the size of the facility all play a role in how the "cleaning" flow pattern is developed. Small rodent facilities without central cage-wash facilities may clean the shoeboxes by hand in a sink located someplace outside the animal room, such as a "procedure" room or a designated washing area where the cages are cleaned by hand either in a sink or with a pressure washer or steam cleaner. Most facilities require a central cage-wash area where mechanical cage-washing machines are used to clean all parts of the cage unit. The most typical flow through the cage-washing facility is from the soiled side, through pass-through washing equipment, into the clean side, where the cages are reassembled and prepared to be taken to the animal rooms. They may first be stored in the clean side of the cage-wash or, preferably, taken to an adjacent clean-cage storage room. Although less effective in preventing cross-contamination, very small facilities may have a single cage-wash room with a single-door mechanical washer. In this case, the flow would be from the corridor into the room, in and out of the cage-washer and then back into the corridor to a storage room. With a single room for washing cages, clean cages should never be stored in the cage-wash room. The centralized cage-wash area may be located near the animal rooms, where the cages can be wheeled to and from the animal room(s), or it may be located on a different floor, requiring elevators, or in a different building, requiring more complicated transport.

In many animal facilities and nearly all rodent-intense animal facilities, autoclaves are inserted into the cage circulation pattern. There are three common locations where one or more two-door pass-through autoclaves, typically floor-loading bulk autoclaves, may be installed: one is in the cage-wash area between the clean and soiled side of the cage-wash area; another is between the clean side of the cage-wash and the sterilized cage storage room; and the third is at the site of a rodent barrier area or a biocontainment area, where they are used to sterilize cages into the barrier or out of biocontainment. With the third option, staging space is required at the entrance to the autoclave and storage/cool-down space is required on the exit side of the autoclave. This option eliminates the need for wrapping cages for delivery from the cage-wash area to the barrier, or from biocontainment to the cage-wash area, significantly reducing labor cost.

D. Equipment

Equipment movement relates primarily to large cage racks. Also, cage-washing and autoclave equipment may need to be moved in during construction or later. It also applies to movement or replacement of old equipment. Storage space for this equipment adjacent to the animal facility would be ideal. The following are some of the issues to be addressed:

- Will the equipment need to pass through animal facilities?
- Are the door openings along the route large enough?
- Are the corridors wide and high enough for the equipment to pass?
- Are there obstructions along the corridors that would restrict passage?
- What are the weight limitations to the floors being traversed?
- If an elevator is required, is it big enough, and is it rated for the weight of the equipment?
- If the mechanical room is on the top floor, can the equipment be introduced through some roof access?

Floor surfaces along the transit route should be protected to prevent damage. Damaged floor surfaces in animal facility corridors need to be repaired to remain in compliance with surface sanitizing requirements.

E. Chemicals and Hazardous Substances

Chemicals and hazardous substances should be stored and moved in accordance with appropriate federal, state and local regulations and guidelines. Bulk chemicals for central cage-washing operations are typically delivered at the dock in 30- to 50-gallon drums or larger bulk containers from where it is stored within the central cage-washing area, preferably in a separate room so as not to impede sanitation of the cage-wash area, or in bulk containers at a remote site, ideally near the dock, from where the chemicals are pumped through pipes to the cage-wash machines. Appropriate spill-containment provisions must be applied wherever the bulk tanks are located. Chemicals should not be stored with feed or bedding. Cleaning chemicals that require frequent mixing for activation and automated mixing devices should be located in the cage-wash area, or in locations within the animal facility where adequate spill containment and splash protection can be instituted. Movement of chemicals from point of receipt to storage should be scheduled when animal activity is not occurring in the same corridors. Movement of hazardous materials should traverse the shortest distance between point of origin and point of use. Depending on the hazardous material in question, chemical, biological or radiological, movement of this material should be closely coordinated with personnel and/or animal contact or movement. How easily that is accomplished depends on the corridor configuration of the facility, and the presence or absence of physical barrier controls. Removal of hazardous waste requires specific storage facilities located adjacent to a dedicated waste-removal dock or point of exit. Facilities/docks for the receipt of animals and feed and bedding should be separate from the facility/dock for waste disposal, including hazardous waste disposal.

F. General Supplies

General supplies, including personal protective equipment (PPE), are usually delivered to the dock and stored in a common storage area. PPE is dispersed from here to multiple PPE stations. This storage facility should be separate from the feed and bedding and chemical storage facilities. Depending on the size of the facility, PPE stations may be located strategically throughout the animal facility, or at the entrance to the facility. These stations may be in the form of mobile carts or, in new construction, built into the walls along the animal corridors. Stations where large amounts of PPE are dispersed should have storage capabilities nearby. This will minimize transport trips from central PPE storage.

III. MOVEMENT OF ANIMALS

A. Into the Facility

Movement of animals into the facility begins at the receiving dock/area. Depending on the geographic location and species received, provisions should be made to protect the animals from weather extremes and from the potential for escape during the receipt process. Depending on the species and the size of the facility, receipt procedures may include physical examination of the animals in the receiving area, as well as surface decontamination of the vendor's shipping container to prevent disease entry from contaminated box surfaces. Some institutions do not allow vendor shipping boxes to be brought into the animal facility, and animals are transferred from shipping box to clean cages at the receiving area. Non-human primates are often transported directly to their designated housing area to avoid the potential for escape in the receiving area. These examination and decontamination processes are performed in a processing area entered from the receiving dock/building entry and connected to a corridor into the animal facility. Where animal facilities are located off of the ground floor, the connection from the processing area may be directly to an elevator. Institutions may provide quarantine or isolation areas as part of or adjacent to the receiving/processing areas where animals are housed under quarantine conditions because of an unknown disease status. This area may contain cubicles (see Chapters 15 and 26) for multiple separations of species or shipments, isolators (flexible or rigid) for strict containment, or just a designated housing space where animals may be held for observation or laboratory screening.

B. Through the Facility

Movement of animals through the facility is dependent on facility location and size, corridor configuration, the animal species, the animal's health status, and institutional policies. Species other than rodents may frequently be moved between animal rooms and animal procedure laboratories in the facility, including surgery and imaging areas. Movement of rodents is typically restricted to dedicated adjacent procedure rooms and special procedure laboratories.

C. Out of the Facility

Institutions may discourage or prohibit the movement of live animals out of the animal facility, including to investigator laboratories. Other institutions may allow live animals to be moved out of the animal facility but not returned. This is frequently the policy applied to rodent movement within a facility. If animals can be moved to laboratories outside the animal facility and this involves passage through public access

space or patient areas, transportation should be in enclosed containers to prevent dispersing animal-related allergens and infectious agents, and to keep the animals out of sight. Rodents may be transported in special disposable carriers or covered micro-isolation cages. Large animals such as dogs, cats and non-human primates can be transported in fully enclosed ventilated mobile transport cages equipped with HEPA filters.

Dead animals should be stored in a refrigerator, following which they are transported to the dock in various types of containers to be disposed of elsewhere. Some animals, especially transgenic rodents, will be transferred live to other facilities at the institution, and a small percentage will be shipped to other research facilities. Both will typically involve transferring the animals in appropriate shipping containers to trucks at the dock. Because animals come and go at the dock, it is highly desirable that the dock be out of public view. Animals should not be transported between buildings or sites in personal vehicles.

IV. MOVEMENT OF PEOPLE

The circulation of people into, within and out of an animal facility will depend on the size and location of the facility, the nature of the research programs it supports, and institutional policies. Personnel entry into the vivarium should be restricted to specific entry portals and controlled by appropriate security methods. These may be in the form of key-card or key-pad entry systems, biometric identification systems, security cameras, lock-and-key systems, or a combination of methods.

There are three basic categories of people who enter the animal facility:

1. Animal-care and other technicians whose primary workplace is the animal facility, where their work is primarily animal related. They generally are required to change from street clothing into a work uniform. Entry through a locker room is a good arrangement for them.
2. Research staff whose primary workplace is in a research laboratory but who periodically enter the animal facility to work with their animals. If they will have animal contact, they may be required to don personal protective equipment (PPE) over their street clothing or work uniform prior to entering the animal facility. This will require an entry vestibule where they can don the PPE.
3. Individuals who will not have animal contact. These include the animal facility administrative staff and individuals having business inside the animal facility administrative area, including people who work for the institution and visitors. The entrance to the administrative area should be outside the animal housing portion of the animal facility but preferably immediately adjacent to it. An arrangement whereby people entering the animal housing area pass by the administrative area is desirable. Entry to the administrative area may or may not be controlled.

Within the animal facility there may be special areas that require controlled access and additional or special PPE, such as rodent barriers, primate housing areas and biocontainment areas. Access and egress for some areas, for example ABSL-3 biocontainment facilities, may be through a dressing/shower room. For those areas of the animal facility that have limited access and strict entry requirements but are subject to regulatory oversight, or may foster public interest for a variety of reasons, design options such as viewing windows or closed circuit TV monitoring that will meet this need without compromising barrier or containment integrity could be considered.

V. CIRCULATION DESIGN AND ITS MANAGEMENT IMPACT

Circulation between the outside world and the animal facility for all but personnel evolves around the dock or docks where animals and supplies are received and trash is discarded – not necessarily the same dock. Circulation patterns within the animal facility for animals and supplies revolve around the dock and storage rooms or animal rooms, and for cages around the cage sanitation facility and the animal rooms. Interior circulation patterns may include both horizontal and vertical circulation. The horizontal circulation strategy is one of the early decisions to be made in the facility planning process. Three basic options are single corridor, dual corridor, or a combination of both. Vertical circulation may be required for a number of reasons, including a multi-floor animal facility, the dock being on a different floor from the animal facility, and user access to the animal facility from the research laboratories.

A. Access and Egress

1. *People*

With the exception of stand-alone animal facilities, the primary entrance to the animal facility for people will most likely be from inside the building in which the animal facility is located. Ideally, the entrance should be convenient to research laboratories that the animal facility is intended to support, because the traffic between the laboratories and the animal facility is likely to be significant. There may or may not be more than one access/egress port for people, but typically there would be one primary port. Entry into the animal housing areas should be strictly restricted to authorized persons, but this level of security need not necessarily apply to the animal facility administrative area. Ideally, the primary port to the animal facility is designed to direct people past the animal facility office area before entering the access-controlled

animal housing portion of the facility. There are many reasons for this, but the primary ones are to make the office area convenient to users of the facility and the animal-care staff while allowing access to those who have business with the office but do not need to enter the animal housing portion of the facility.

All people-entry portals, primary and secondary, along with the dock should be controlled by appropriate security methods, preferably an automated security system, and ideally one utilizing biometric readers. Cameras also enhance security.

2. *Materials and Trash*

A dedicated, strategically located and well-designed receiving and shipping area is a critical component of all animal facilities. Ideally, it should have direct access to the animal facility. In a medium to large facility, this is a busy area where large volumes of animals, feed, bedding, sanitation supplies and other supplies are received, much of it on pallets. Shipping of animals is often necessary, especially in an animal production facility and research facilities that invest heavily in producing unique transgenic and knockout rodents. In addition, a large amount of waste material, including soiled bedding, general trash and animal carcasses, is typically generated in animal facilities that need to be transported out of and away from the facility. Ideally, a separate dock, or at least an isolated portion of the receiving/shipping area, should be provided for trash disposal.

The dock may be at street level or one level below, with a ramp between the street level and the dock. The dock should be designed to accommodate a wide variety of delivery vehicle sizes, from vans to 18-wheelers. The standard dock height of 48" is acceptable, but some institutions with multiple facilities may operate trucks with a lower bed, in which case a dock height that is level with the institution's trucks may be more convenient. Regardless of the dock height, a recessed scissor lift that can range from being level with the ground in front of the dock to 54" above the ground is recommended, and certainly is more useful than a hinged load-leveler. The number of bays required will depend on many factors, including the size of the facility, whether or not it is a stand-alone facility or one that supports other facilities, and how animal bedding will be handled. Automated clean and soiled bedding handling systems will require space at the dock or somewhere else that large trucks can access.

An overhang extending at least 6 feet out from the vehicular edge of the dock is required to prevent animal and supplies from getting wet in inclement weather. Consideration should be given to enclosing docks that are exposed to a high volume of public traffic and/or are located in cold climates. In addition to a standard hinged door for personnel entrance, automatic roll-up doors are recommended. In some climates, flying insect air shields may be required.

Immediately inside the dock should be an enclosed climate controlled receiving/shipping area. Adjacent supporting spaces may include a room with animal cubicles for short-term holding of rodents and similar small animals in shipping containers until they can be delivered to an animal room or picked up for shipment, a room for processing and short-term holding of large animals such as non-human primates, dogs, sheep, pigs, etc., and a small office for processing paperwork and digital data entry. Depending on the local situation with regard to waste removal, standard storage space for trash and refrigerated storage space for animal carcasses and hazardous wastes may be required. If elevators are needed to access the animal facility, one or two freight elevators will be located in this area (see below).

B. Horizontal Circulation (Corridors)

The most important internal circulation pattern in an animal facility evolves around the cage sanitation area and the animal rooms, and is usually designed using the following corridor concepts.

- single corridor;
- dual corridor (clean/dirty corridors or research/animal-care corridors);
- combination of single and dual corridors.

1. *Single Corridor*

Single-corridor circulation patterns relative to the cage sanitation area may be unidirectional or bidirectional. In small animal facilities with a limited overall footprint, bidirectional single corridors are generally employed. A typical arrangement in a small facility is to have one double-loaded corridor with all rooms opening onto it and the cage-washing area located at one end or in the middle of the corridor. In such designs the cage-wash area may be a single room in/out design or, preferably, a dual-sided clean/dirty pass-through design. In facilities where there are two doubled-loaded corridors with a central bank of back-to-back rooms between them, the cage-wash area should be centrally located in the central bank of rooms with a pass-through clean/dirty cage-wash area designed with the clean and dirty sides accessible from both corridors. This arrangement allows the flexibility of operating either a unidirectional or a bidirectional cage circulation pattern. Efforts to prevent cross-contamination must focus primarily on operating procedures and, to a lesser degree, the relative air pressures between the animal room and the corridor (see Chapter 34).

2. *Dual Corridors*

Corridor systems are important design features affecting the flow of materials and personnel throughout the facility. Dual-corridor systems, clean and soiled, are sometimes employed. The design concept of dual corridors for research animal facilities was introduced in the 1950s, and by the 1960s it had become the mark of a contemporary research animal facility

(McPherson, 1980; Hessler, 1999). They were and are considered to be an especially useful design for rodent barrier and biocontainment facilities. The primary purpose of the dual-corridor system is to control contamination by directional flow of air, material and personnel from clean, uncontaminated space toward potentially dirty, contaminated space (Hessler, 1991). Secondarily, dual corridors may facilitate a more orderly, less congested flow of materials and personnel through the facility. Strict adherence to flow of materials and personnel to maintain the integrity of the dual system may reduce staff productivity, requiring staffing levels to be increased. Dual corridors also take up a lot of space that could otherwise be incorporated into additional program space. Additionally, personnel often do not utilize them as intended, compromising the intent of the system. The downsides of dual corridors, then, are increased construction cost, increased operating cost, reduced program space, and them not being used as intended. As the years progressed and the square footage cost of animal facilities increased, and alternative management procedures were developed and tested over time (especially microisolation cages), the cost-effectiveness of dual corridors received more careful consideration and, while still desirable if not even highly desirable, dual corridors are no longer considered a must for contemporary research animal facilities.

Dual-corridor plans for animal facilities can take many configurations, but all have one thing in common: the animal rooms are arranged between two corridors with a door to each. There can be multiple layouts for dual-corridor systems, the most basic of which are two- and three-corridor plans. Figure 9-2 is an example of a three-corridor system. A more complex arrangement would be clean and soiled corridors "connected" by alternating clean and dirty crossover corridors with animal rooms off the crossover corridors (Figure 9-3). Traditionally, the corridors are referred to as "clean" and "dirty." All clean cages and supplies are transported through clean corridors, and all supplies are stored in rooms off clean corridors; all soiled cages and trash are transported through dirty corridors to the cage-wash area or to the final disposal point and are stored, when necessary, in rooms off dirty corridors. The objective is to decrease the potential for cross-contamination between animal rooms by maintaining separation between clean and soiled cages and supplies. In theory, dual corridors should be superior in terms of reducing cross-contamination; however, when compared to single corridors, they come at a high cost in terms of the ratio of circulation space to assignable space. Figure 9-2 illustrates this point, while the rodent barrier facility illustrated in Figure 9-3 provides an extreme example, in which the corridor space is 39 percent of the total net square footage (all that is shaded in the figure, including the clean corridor) and is equal to 65 percent of the net assignable space (shaded space other than corridors). The small size of the animal rooms (154 square feet) contributes significantly to this inefficiency. If it had been designed with the same clean and soiled corridors at the top and bottom but with "single" crossover corridors, which would have eliminated four of the eight crossover corridors, the mouse cage-housing capacity of 10,000 could have been increased by approximately 30 percent. Whether or not dual corridors are cost-effective is a complex issue, and the answer will vary according to the relative weight assigned to each of the pros and cons, and whether or not there are objectives other than contamination control. Table 9-1 lists some of the major pros and cons of dual corridors as compared with single corridors. In addition to considering the advantages and disadvantages of dual corridors, their limitations as well as alternatives for contamination control should be considered (Hessler, 1991). For example, micro-isolation caging combined with sound micro-isolation cage management techniques have proven to provide a very effective first-level "barrier" for housing rodents, greatly reducing cross-contamination between cages in a room and reducing the concern for cross-contamination between rooms. Circulation may be affected using single-corridor systems, with rooms facing main corridors or rooms off secondary corridors in suite arrangements. Single corridors can and do work when used in conjunction with good programs of animal care, and many institutions have operated animal facilities effectively using single-corridor systems. Room suites provide opportunity for compartmentalization of the facility according to function or program.

A dual-corridor plan is a good, and for many a preferred choice, if cost and space are not issues of concern; however, given that single-corridor systems have proven effective in all types of animal facilities, including barrier and biocontainment facilities where preventing cross-contamination is especially important, choosing to use a single-corridor plan can be a reasonable choice.

a. Management Options for Dual Corridors

While "clean/dirty" is at the root of the dual-corridor design concept, it has evolved to be used in other ways that basically amount to different management options. Management styles may focus on clean/dirty separation, separation by activity, or a combination of both. While all the management options listed below involve dual-corridor designs, the management style chosen may impact facility design with respect to cage flow in and out of cage-wash, and access and egress for personnel. Therefore, a decision regarding management style is best made during the programming phase of the project.

Option 1a – the classic clean/dirty separation for cages and people. With this style, the flow of cages and people is similar. Starting from the clean side of cage-wash, cages are transported through clean corridors, into an animal room, out of the animal room, through soiled corridors, into the soiled side of cage-wash, through the cage-washers, and back to the clean side of cage-wash. With the purest form of this management option, people enter a dressing room where they leave their

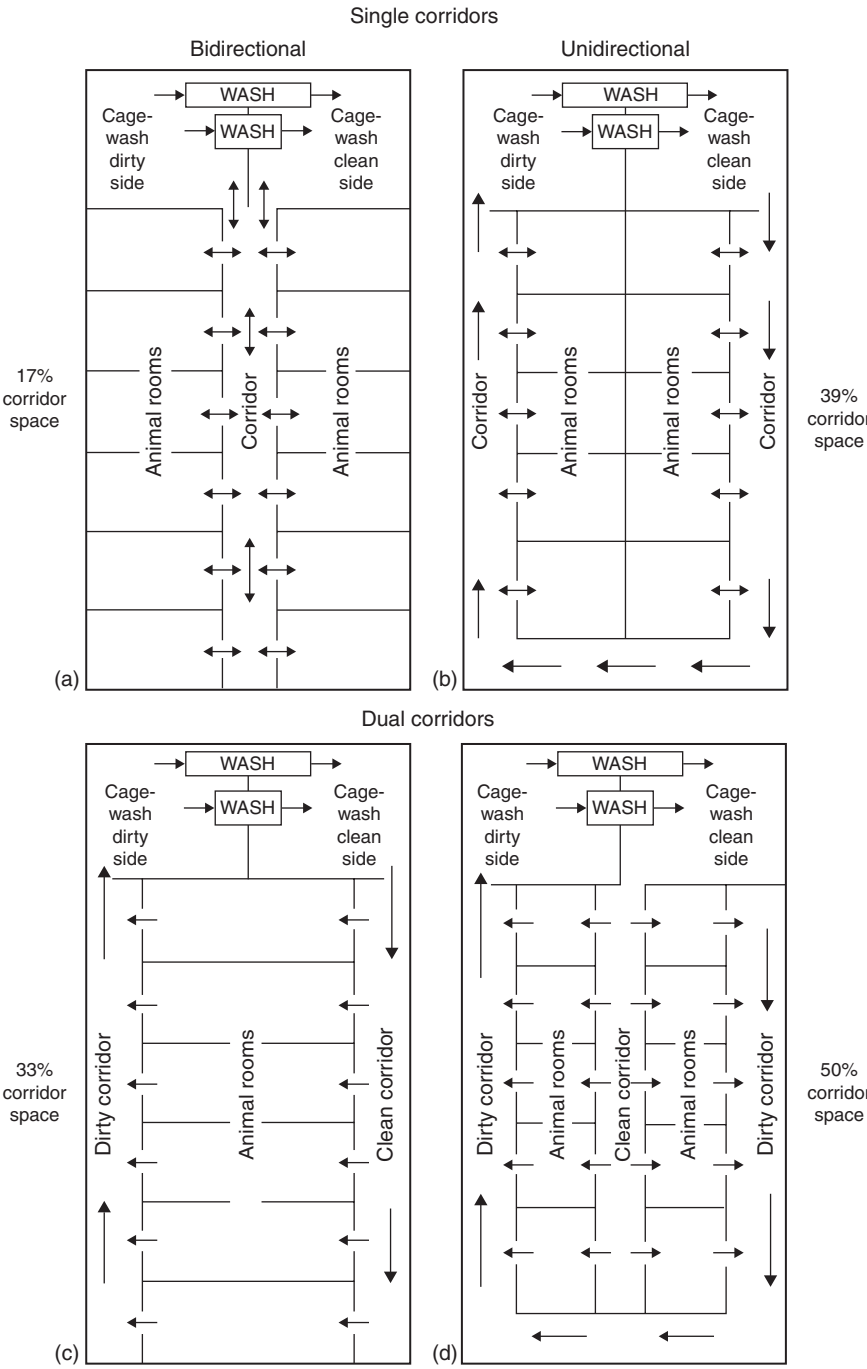

Fig. 9-2 Four examples of circulation patterns within identical footprints are shown with arrows pointing in the direction(s) of traffic flow around the cage-washing area. (A) illustrates a single corridor bidirectional flow pattern; (B) a single corridor unidirectional flow pattern; (C) a dual corridor flow pattern with large animal rooms; and (D) a dual corridor flow pattern with smaller animal rooms. The percentage of the footprint occupied by corridors (shaded areas) is shown for each pattern. These percentages only serve to illustrate the impact of circulation pattern choices, and do not apply to any specific floor plan.

clothes in lockers, pass through a shower, don supplied garments on the other side of the shower, enter a clean corridor, then enter an animal room, exit the animal room into a soiled corridor and then return to the dressing room where they change their clothes. Only one animal room is entered, after which personnel must recycle through the locker/shower room before entering another animal room.

Option 1b – similar to Option 1a, but less "pure" although more practical. With this option animal-care technicians are split, with some working exclusively on the clean side and others on the soiled side. Technicians on the clean side transport cages from the clean side of cage-wash to the animal room, where they change the cages and push the dirty cages into the dirty corridor. When finished in the animal room, they may enter another

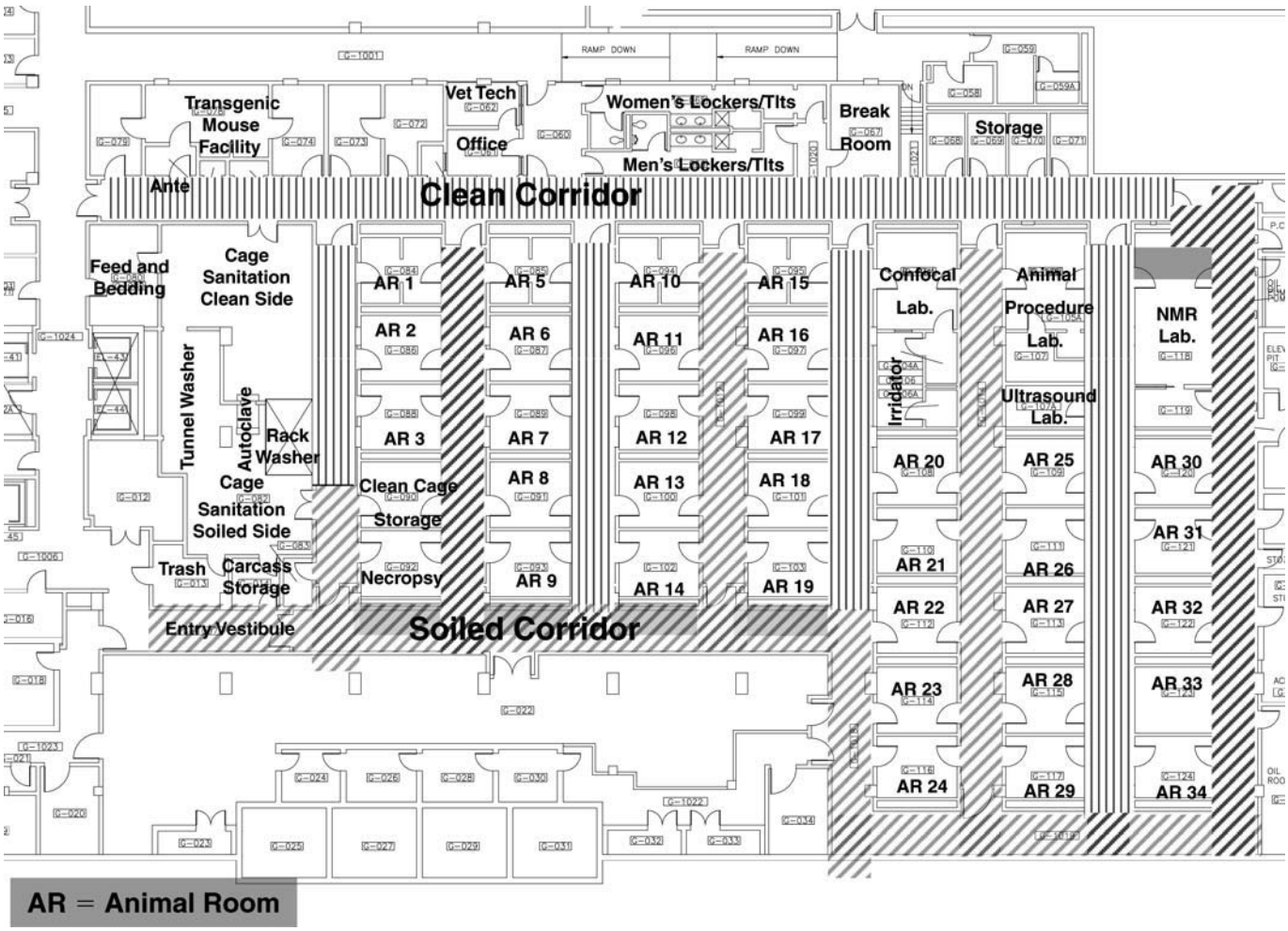

Fig. 9-3 Schematic of a dual-corridor rodent barrier facility in which the corridor space is 39 percent of the total net square footage and is equal to 65 percent of the net assignable space (space other than corridors). This is an extreme example of the spatial inefficiency of dual corridors. The small size of the animal rooms (154 square feet) contributes significantly to this inefficiency.

animal room via the clean corridor. Animal-care technicians working on the soiled side transported the cages to the soiled side of cage-wash. Research staff enter via the clean corridor, going in and out of animal rooms from the clean corridor and then, after working in the last animal room, exit the facility via the soiled corridor. Animal-care staff enter the animal facility after showering (or not) and donning a uniform as in Option 1a. Research staff either enter the same way as the animal-care staff or through a gowning/de-gowning vestibule, where they don PPE over their street clothes or work uniform before proceeding into the clean corridor.

Option 2 – separation by function. With this management style, all the animal-care staff work exclusively off one corridor and all the research staff off the other corridor. For example, in a three-corridor layout, research staff may work out of the central corridor and animal-care staff out of the lateral corridors. From the animal-care point of view, this is no different than a single-corridor facility design. With either a three- or a two-corridor layout, this management option works especially well when there is a procedure/anteroom between the research staff corridor and the animal room, with a door to both. Animal-care staff enter the facility through a locker room, where they change from street clothes into a work uniform. Research staff enter through a gowning/de-gowning vestibule, where they don PPE over their street clothes or work uniform before proceeding into the "investigator corridor," from which they may enter and exit multiple animal rooms. Both animal-care and research staff may or may not be required to change PPE between animal rooms.

TABLE 9-1

ADVANTAGES AND DISADVANTAGES OF A DUAL-CORRIDOR DESIGN AS COMPARED WITH A SINGLE-CORRIDOR DESIGN

Advantages
• Avoids the mixing of clean and soiled cages and supplies in the corridor, thus reducing the potential for cross-contamination
• Facilitates the movement of cages, supplies and people throughout the facility
• When managed to separate activates by having all animal=care activities performed off one of the dual corridors and investigator activities off the other corridor, productivity on both sides can be increased
• May be superior to single-corridor systems for controlling airborne contaminants, although both have the same limitation because differential air pressures across a door are essentially zero when the door is open and air randomly moves between the adjoining spaces
Disadvantages
• High cost in terms of additional space that dual corridors require
• Reduced number of animals that can be housed in a given footprint
• Two doors in the animal room reduce the usable space in the room
• Because the space inefficiency of dual corridors is accentuated by having small rooms, it drives the design toward large rooms when smaller rooms may (although not necessarily) facilitate more efficient use of animal housing spaces (note "C" and "D" in Figure 9.2)
• Increased labor costs when managed as a true clean/dirty system, especially when a shower and/or a change of uniforms is required before entering each animal room.

Option 3a – a combination of separation by clean/dirty and by functions. With this management style, animal-care staff split duties between the clean and dirty corridors in the same way as in the clean/dirty style described in Option 1b. The difference between this option and Option 1b is that the research staff work exclusively off of the clean corridor. Typically, with this management option, animal-care staff enter the facility through a locker room, where they change from street clothes into a work uniform. Research staff enter through a gowning/de-gowning vestibule, where they don PPE, typically over their street clothes or work uniform, before proceeding into the clean corridor, from which they may potentially enter and exit multiple animal rooms. Both animal-care and research staff may or may not be required to change PPE between animal rooms.

Option 3b – identical to Option 3a, except that the research staff work off of the soiled corridor.

b. Air Balancing

Air balance in facilities with dual corridors is typically designed with the clean corridor positive to the animal room, and the animal room positive to the soiled corridor (see Chapter 34).

3. *Combination of Single and Dual Corridors*

Combination dual- and single-corridor designs may be employed in larger facilities where special housing areas (such as a non-human primate area), special research program areas, biocontainment or barrier areas are isolated but utilize the animal-care support services of the main facility, such as cage sanitation and storage facilities. These "special" areas may utilize a dual-corridor design while the rest of the facility utilizes a single-corridor design, or *vice versa*.

4. *Architectural Features of Corridors*

Corridors must be wide enough to accommodate potentially heavy traffic consisting of cages, cage racks, supplies (some on pallets), and both care staff and research staff, sometimes all at the same time. Typical recommended widths are 7–8 feet for single-corridor facilities and 6–7 feet for dual-corridor facilities. When deciding between having a 7-foot or an 8-foot wide corridor, the inclination automatically to scrimp on the corridor width in favor of the animal room size should be resisted until it can be determined that 6" more added to room on each side of a double-loaded corridor will significantly enhance how the rooms function, including animal housing capacity. If it doesn't make a significant difference, the space generally will be more useful in the corridor.

Objects that protrude into the corridor are vulnerable to damage from cage racks being transported through the corridor, and should be avoided. Wall-mounted equipment should be recessed into the wall, or mounted higher than the highest cage racks, or, as a last resort, protected with crash guards. All corridor walls should be built with impact-resistant materials and protected with guard rails. A common mounting height for guard rails is 32–36" off the floor, but many consider a mounting height of 6–10" off the floor to be more effective because it will protect the walls from cage racks and carts of any height, including low carts such as platform carts and bottle-basket carts commonly used in animal facilities (Figure 9-4). Guard rails should not only be durable, because they will take a beating; they must also be designed to facilitate sanitation

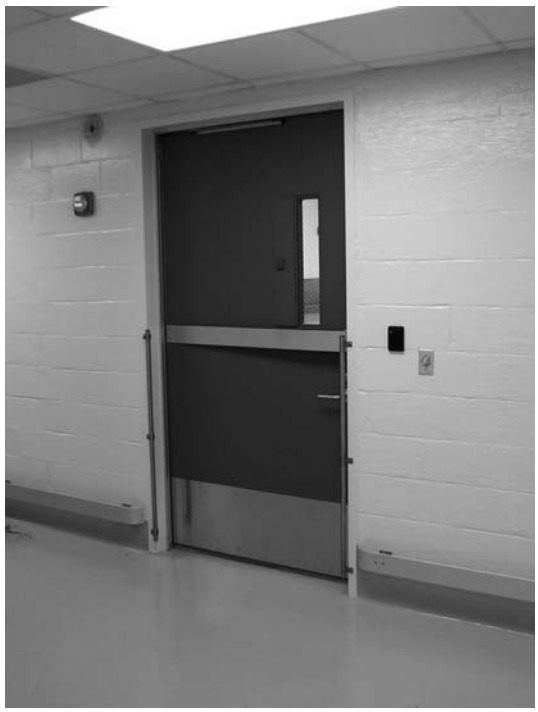

Fig. 9-4 Picture of an animal facility corridor illustrating guard rails installed approximately 6" off the floor. Note also the crash rail on the door and the vertical door-frame guards.

and eliminate harborage sites for insects and vermin. Another effective design for protecting walls is a slanted concrete base extending 6" out from the wall at the floor (point A) and 6" up the wall from the floor (Point B), with a straight line connecting points A and B. The finish floor material should seamlessly cover the base (Figure 9-5).

In addition to corridor width, the width and height of all doors in the circulation pattern for all equipment and supplies must be carefully considered. This includes not only doors into and out of animal rooms, cage-wash rooms and storage rooms, but also dock doors, corridor firebreak doors, cage-washing equipment doors and elevator doors. In addition, all doors through which cage racks will routinely pass should be automatic doors, including corridor doors and cage sanitation and cage-storage related doors.

C. Vertical Circulation – Elevators/Ramps/Stairwells

1. *Elevators*

Ideally, animal facilities are located on levels that have direct access to ground-level transportation, and where that access is from inside the animal facility. Elevators within the animal facility are required when the animal facility has more than one floor and/or when the dock is on a different floor than the animal facility. Designing elevators into an animal facility should be based on the same criteria as are used in selecting

Fig. 9-5 Picture of an animal facility corridor illustrating 6" × 6" sloped bases designed to protect the walls. The bottle cart and cage rack show how the base serves to protect the wall. They also show how the low-mounted crash rail in Figure 9-3 would effectively protect the wall from being hit by either short or tall carts.

corridor design; movement of caging from animal room to cage-wash area, separation of personnel from cage movement as much as possible, and contamination control.

When elevators are required to support routine daily animal-care operations, a minimum of two dedicated freight elevators is highly recommended, especially if an elevator is required for transporting cages to and from a cage-wash area. One elevator is used for transport of clean cages and supplies, and one for soiled cages, trash, and potentially contaminated items. They both may be used for transporting animals, depending on the species and their microbiological status (e.g., rodents on the clean elevator and most other animals on the dirty elevator). Even more importantly, two elevators are essential so that at least one is available when the other is out of service. Routine animal care in such a facility cannot be maintained without a functioning elevator. Of course, the elevators must have independent mechanical and electrical systems, and be supplied with emergency power.

When it is necessary to use elevators to transport cages between animal rooms and the cage-wash area, one of the two elevators should be designed to operate between a "clean" corridor near the clean side of the cage-wash, and a clean corridor on each animal-housing floor. The other elevator should operate between a "dirty" corridor near the dirty side of the cage-wash and a "dirty" corridor on each animal-housing floor. An area for staging and receiving cage racks and supply carts is required in front of the elevators on each floor. An alternative site for the elevators could be inside the dirty and clean sides of cage-wash; however, with elevators opening in to the cage-wash area there is the concern that the "syringe" action of elevators may more readily serve to spread diseases throughout the facility.

When an animal facility is located on other than the ground floor of a multi-storey building and the only use of the elevators is to move animals, supplies and trash between a small animal facility and the dock, then one dedicated freight elevator may be adequate so long as an alternate elevator accessible from the dock and the animal facility is available elsewhere in the building for use when the animal facility elevator is out of service. With very small animal facilities (e.g., a few animal rooms), a common building freight elevator and personnel elevators may be the only reasonable design option. In that case, the freight elevator should be equipped to allow the vivarium staff to lock out the elevator when animals, dirty caging or trash are being transported between floors. In this case, it is best if the freight has a double-door configuration with "key" control entry into the animal facility.

The vertical movement of elevators in the elevator shaft acts as a syringe, sucking and pushing air through elevator doors on each floor. This can significantly influence air balance on the floors serviced by the elevator. Efforts should be made to mitigate this by whatever means available, including creating vestibules or air locks between the elevator doors and critical areas such as rodent barriers and biocontainment areas.

Some multilevel facilities may require people elevators within the animal facility, depending on the availability of elevators elsewhere in the building and whether or not there is access to the animal facility on each floor. Certainly, multilevel animal facilities will require internal people elevators if the entire building is an animal facility. Preferably, the general-use personnel elevators should not open directly into the animal facility. If they do, the elevator door must be equipped with the same access control features as planned for all entry ports.

All elevators used for animal-care purposes should be constructed of durable materials and crash guards that allow appropriate decontamination as required.

2. *Ramps*

Depending on building elevations, the use of ramps between animal areas may be appropriate to conform to ADA requirements for personnel working in the facility. Ramps are also useful at receiving dock locations where an elevated truck dock is employed.

3. *Stairways*

Stairways that allow entrance into an animal facility should be equipped with access control security devices the same as at the other entry ports to the facility, to prevent unauthorized entry and the risk of disease contamination to the colony. Stairwells that open to the outside should be constructed with a sealed entryway to prevent vermin and insects from entering the animal facility, and prevent outside weather conditions from impacting on facility air-balancing and -pressure differentials. Ideally, stairwells should not lead directly into the animal facility; however, when they do, they should lead into clean corridors where possible. Emergency stairwells that lead to special areas (e.g., barrier and biocontainment areas) should be alarmed to prevent unauthorized entry. Stairways should be provided with emergency lighting, and conform to the appropriate fire codes for construction.

VI. CONCLUSION

Some of the earliest decisions to be made in the planning process involve circulation issues both outside and inside the animal facility. The most important circulation issues outside the animal facility are the primary and secondary (if any) people portals to the animal facility, and the location of the dedicated dock required to service the animal facility. The most important decisions within the animal facility are the type of corridor system to be designed (single or dual), and the location of elevators and stairwells if required. Each corridor system has advantages and disadvantages. The amount of weight applied to each will determine the choice; both are used in contemporary animal facilities. It is preferred to avoid vertical circulation when possible, but when it is necessary to transport cages between animal rooms and cage-wash, two dedicated freight elevators should be provided; one for transporting clean cages and materials, and one for transporting soiled cages and trash. Most importantly, two elevators are required to better assure uninterrupted animal care by having at least one elevator available when the other is out of service.

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Chapter 10

Functional Adjacencies

Jack R. Hessler

An integral part of planning an animal facility is to establish priorities for how each of the spaces programmed for the facility should physically relate to every other space in the facility. There is no set pattern. Priorities will vary according to many factors, including the species to be housed, size of the facility, circulation patterns to be used, equipment to be used and, like many other aspects of planning and designing, the experience and opinions of the individuals involved in planning the facility.

Close-proximity priorities generally evolve around issues of convenience, e.g., designing administrative space, training space and diagnostic laboratory space close together; animal housing rooms and cage sanitation as close as practical; bedding storage close to the clean side of the cage sanitation area; and large animal housing and surgery areas as close to one another as practical.

Separation priorities generally evolve around one of two objectives: (1) separating noise-generating areas (e.g., cage sanitation and dog housing areas) from other animal rooms and from spaces occupied by people (e.g., offices, laboratories, break areas, etc.); (2) separating microbiologically "clean" areas or animals from areas or animals that potentially are not microbiologically "clean" (e.g., rodent barrier from rodent quarantine).

The cage sanitation area is an example where the close proximity between the clean and soiled sides is a given but where separation is a must to prevent microbial cross-contamination, which is accomplished by physical barriers rather than distance. Placing spaces other than those that will be occupied by animals or people around a noise-generating area is an example of using both distance and physical barriers to achieve separation.

Table 10-1 illustrates a grid for communicating desired priorities in a facility program by establishing five levels of proximity priorities:

1 = proximity close with high priority;
2 = proximity as close as practical;
3 = no proximity priority;
4 = separation as much as practical;
5 = separation with high priority.

It also provides an example of how adjacency priorities could be established for an animal facility with the types of spaces listed; however, it is not necessarily intended to suggest how relationships should be prioritized. Chapter 9 in this book also addresses the issue of functional adjacencies from the standpoint of the movement of people, supplies and equipment through the facility.

TABLE 10-1
COMMUNICATING PRIORITIES FOR FUNCTIONAL ADJACENCIES IN RESEARCH ANIMAL FACILITIES

	Main entrance	Administrative/office area	Conference/training area	Locker/dressing/shower/restrooms	Technician break area	Diagnostic laboratories	Necropsy	Surgery	Veterinary clinical support area	Imaging laboratories	Animal procedures labs (multiple)	Cage sanitation area	Bedding storage	Feed storage	Supply storage	Bulk chemical storage	Animal carcass storage	Housekeeping storage	Janitorial service closets (multiple)	Conventional small-animal housing	Conventional large-animal housing	Rodent barrier area	Biocontainment area	Chemical & nuclear containment	Rodent quarantine	Dock/receivings/shipping area
Main entrance		1	1	2	2	2	5	3	3	3	3	4	3	3	3	3	5	3	3	3	4	3	3	3	3	4
Administrative/office area	1		1	2	2	2	4	2	3	3	3	4	3	3	3	3	5	3	3	3	4	3	3	3	3	4
Conference/training area	1	1		2	2	2	4	2	3	3	3	4	3	3	3	3	5	3	3	3	4	3	3	3	3	4
Locker/dressing/shower/restrooms	2	2	2		1	3	4	3	3	3	3	4	3	3	3	3	5	3	3	3	3	3	3	3	3	3
Technician break area	2	2	2	1		3	4	3	3	3	3	4	3	3	3	3	5	3	3	3	4	3	3	3	3	3
Diagnostic laboratories	2	2	2	3	3		2	3	2	3	3	4	3	3	3	3	5	3	3	3	3	3	3	3	3	3
Necropsy	5	4	4	4	4	2		3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	2
Surgery	3	2	2	3	3	3	3		2	2	3	4	3	3	3	3	5	3	3	3	1	3	3	3	3	4
Veterinary clinical support area	3	3	3	3	3	2	3	2		2	3	4	3	3	3	3	4	3	3	3	1	3	3	3	3	3
Imaging laboratories	3	3	3	3	3	3	3	2	2		3	3	3	3	3	3	4	3	3	3	1	1	3	3	3	3
Animal procedures labs (multiple)2	3	3	3	3	3	3	3	3	3	3		4	3	3	3	3	4	3	3	1	1	1	1	1	1	3
Cage sanitation area	4	4	4	4	4	4	3	4	4	3	4		1	1	3	3*	5	3	3	2	2	2	2	1*	2	3
Bedding storage	3	3	3	3	3	3	3	3	3	3	3	1		2	3	3	5	3	3	3	2	2	2	2	2	3
Feed storage	3	3	3	3	3	3	3	3	3	3	3	1	2		3	3	5	3	3	3	3	3	3	3	3	3
Supply storage	3	3	3	3	3	3	3	3	3	3	3	3	3	3		3	4	3	3	3	3	2	2	3	3	3
Bulk chemical storage	3	3	3	3	3	3	3	3	3	3	3	3*	3	3	3		3	3	3	3	3	3	3	3	3	1
Animal carcass storage	5	5	5	5	5	5	2	5	4	4	4	5	5	5	4	3		3	3	3	3	3	3	3	3	1
Housekeeping storage	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3		3	3	3	3	3	3	3	3
Janitorial service closets (multiple)4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3		3	3	3	3	3	3	3
Conventional small-animal housing	3	3	3	3	3	3	3	3	3	3	1	2	3	3	3	3	3	3	3		4	4	4	3	4	5
Conventional large-animal housing	4	4	4	3	4	3	3	1	1	2	1	2	2	3	3	3	3	3	3	4		3	3	3	3	2
Rodent barrier area	3	3	3	3	3	3	3	3	3	1	1	2	2	3	2	3	3	3	3	4	3		4	3	5	4
Biocontainment area	3	3	3	3	3	3	3	3	3	3	1	2	2	3	2	3	3	3	3	4	3	4		3	3	4
Chemical & nuclear containment	3	3	3	3	3	3	3	3	3	3	1	1*	2	3	3	3	3	3	3	3	3	3	3		4	3
Rodent quarantine	3	3	3	3	3	3	3	3	3	3	1	2	2	3	3	3	3	3	3	4	3	5	3	4		2
Dock/receiving/shipping area	4	4	4	3	3	3	2	4	3	3	3	3	3	3	3	1	1	3	3	5	2	4	4	3	2	

Proximity/priorities: 1 = close/high; 2 = close/medium; 3 = no priority; 4 = separation/medium; 5 = separation/high

1*- The exit for cages from the Chemical & nuclear containment area should enter directly into the soiled side of the cage sanitation area so that the cage- and rack-washer can be used to decontaminate the cages when codes permits.

2- Animal procedure labs are to be scattered throughout all the animal housing areas.

3*- Bulk chemical storages in best located at the dock with chemicals piped to the cage-washers. If not, then the bulk chemical storage should be in a separate room in the cage sanitation area.

4 - Janitorial closets area to be scattered throughout the facility and within special areas such as surgery, biocontainment, barriers, etc.

Chapter 11

Vivarium Esthetics and Visual Design

Josh S. Meyer and J. Erik Mollo-Christensen

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Vivaria are among the most functionally-driven parts of a research enterprise, and challenge owners and architects to provide visually interesting and humane spaces for people. The complexity and cost of designing and constructing the technical requirements of a vivarium for animal research often eclipse visual design, but by applying the basic principles of esthetics and design, architects can create attractive and comfortable environments for investigators and animal-care staff.

With the continued expansion of biomedical research into translational medicine, genetics, proteomics and regenerative medicine, the use of animal models has expanded as well, and the proportion of both space and time devoted to animal studies has increased correspondingly. Vivaria have become extensions of the laboratory, evolving from simple core support functions into an integral part of the research program, and designing all spaces to support and enhance the laboratory experience applies as much to vivaria as to laboratories and office space. Animal facilities may be located in obscure or concealed parts of a building, but even below-grade locations can offer design opportunities, and vivaria in all locations can benefit from attention to visual design.

I. THE IMPORTANCE OF DESIGN: THE VIVARIUM AS A LABORATORY ENVIRONMENT

Although vivaria are used primarily to house animals, these facilities have become the primary work location for the humans who work with them, and for many their primary laboratory space. The increased use of immunocompromised and transgenic animals housed in barrier conditions requires that the investigators come to the animals, rather than the reverse.

This has increased the human population within vivaria to include not only animal-care staff but investigators as well, many of whom spend most of their working time in the vivarium, and use it as their primary laboratory.

Good design is as important in vivaria as it is in laboratory space, to provide a high-quality work environment for the scientific staff. Most research institutions have in many respects become business enterprises, and the competition to attract and retain staff is considerable. Investment in facilities that meet both functional and visual needs has become a necessary part of an institution's business plan. The appearance and design of a research building is often a distinguishing factor in the attractiveness of an institution to an investigator or donor, and research buildings have become architectural features of academic and institutional campuses and a part of the overall image of the institution.

A well-designed laboratory and vivarium facility conveys a commitment by the institution to high-quality research and working conditions, as well as a commitment to core research functions. The visual design and appearance of both laboratories and vivaria are part of an image of a well-managed research enterprise and good animal care, and express a high quality of life for the staff. The ability of well-designed space to improve satisfaction and productivity is elusive to prove scientifically. Ironically, the enrichment of non-human primates, which has been studied extensively (see, for example, *The Psychological Well-Being of Non-Human Primates*, National Academy Press, Washington, DC, 1998), but it is generally acknowledged that good physical working conditions are always a positive influence, and can enrich the human primates in many ways.

II. FUNCTIONAL AND PLANNING CHALLENGES

Most aspects of vivaria are controlled by functional needs, which inherently limits some aspects of visual design. These include repetitive spaces, dimensional uniformity, materials and lighting, which have traditionally resulted in a monotonous visual quality. Additionally, the premium cost of building and operating vivarium space over typical wet laboratories encourages highly efficient space planning and maximum housing space in proportion to people space. All of these factors are strong influences on design decisions, and can discourage creative design and interesting materials. Some of the specific challenges are discussed below.

A. Plan Organization and Layout

- *Space efficiency*: high construction cost and indirect cost recovery principles for funded research encourage maximum space efficiency.
- *Material movement*: heavy traffic of carts, cage racks and materials encourages simple and rectangular corridor patterns.
- *Work flow protocols*: specific patterns of work flow for animals, materials and people, based on clean/dirty separation and cross-contamination, often result in visually confined spaces and difficult orientation and wayfinding.

B. Room Types

- *Housing/holding rooms*: these are usually repetitive and uniform in size and shape for maximum flexibility, which encourages rectangular layouts and long, uniform corridors.
- *Corridors*: these are usually wide for material and rack movement; the primary goal is usually physical abuse resistance.
- *Procedure and operating room spaces*: these are usually repetitive and rectangular to accommodate casework and equipment, as well as possible conversion to housing use.
- *Cage-wash areas*: these are usually the most spacious single rooms, but are dominated by material flow and washing equipment functional needs, and by the most severe finish material requirements.
- *Break areas*: these are usually inside the vivarium perimeter and subject to the same cleanliness needs, as well as hard surfaces and durable materials.
- *Offices*: these are subject to the same hard surface and cleanliness requirements when inside the vivarium for technicians and staff.

C. Other Challenges

- *Vivarium location*: vivaria are often relegated to basement or other invisible locations for security reasons or because of the higher priority of "people" spaces.
- *Lighting*: this must be uniform and within specific illumination levels and color temperature ranges for animal housing conditions, and the need for durability, cleanability, and contamination resistance also limits fixture types and visual interest.
- *Daylight*: this is precluded for animal housing spaces with photoperiod requirements, and often restricted for security reasons of visibility or physical intrusion.
- *Security*: strict protocols and access control inherently compartmentalizes the vivarium and limits visual openness, and security hardware and devices increase the overall technical and functional appearance.
- *Furniture*: seating and work surfaces are subject to cleanliness requirements and hard surfaces.
- *Artwork and decoration*: this is usually discouraged due to hard-to-clean surfaces and clutter.

D. Material Challenges

Finish materials have highly functional and prescriptive requirements, and the palette of materials and colors is

often limited. The *Guide for the Care and Use of Laboratory Animals* and other statutory and regulatory requirements, as well as the requirements and standards for AAALAC (Association for Assessment and Accreditation of Laboratory Animal Care) certification, dictate essential performance requirements that inherently limit material choices. Materials are always selected for sanitary and durability aspects, resistance to cleaning agents and contaminants, and for having smooth hard surfaces that do not harbor vermin.

As a result, most vivaria have a highly functional and sterile appearance, similar to hospital operating suites and sterile processing areas. Smooth surfaces, stainless steel and white epoxy paint often create the predominant esthetic because they work, and descriptions such as "warm" or "comfortable" are rarely used. There are opportunities for variety and color with many materials; some of the specific issues are the following:

- *Flooring*: this is usually monolithic resinous such as epoxy or methyl methacrylate (MMA), or welded seam vinyl or other resilient materials with limited color ranges and higher cost of multiple colors or patterns.
- *Wall materials*: whether concrete masonry units (CMU) or gypsum wall board (GWB), the material is less important than the coating or covering that provides the finish appearance.
- *Paint*: this is usually an epoxy or other high-performance coating; the color range is almost infinite, but light and color rendition in housing and procedure spaces may limit choices.
- *Wall coverings*: fiberglass-reinforced plastic (FRP) and other welded-seam sheet materials provide excellent performance, but have a limited color range.
- *Ceramic tiles*: these are often limited to shower and locker areas, but are available in a wide variety of colors.
- *Ceilings*: smooth cleanable materials are limited to gypsum wallboard, smooth lay-in tiles and FRP, all of which have a limited color range except for paint.
- *Doors*: these are generally limited to painted hollow metal, stainless steel or FRP, as clear-finished wood is not durable enough in most areas.

Fortunately, some of these materials are available in many colors. Paint in particular has the widest range, and epoxy coatings can be tinted as desired. Epoxy flooring is essentially the same material used as thin-set epoxy terrazzo in non-vivarium uses, and can be patterned and colored. Even with specific color requirements in housing and procedure areas, other spaces can be designed for variety and visual interest without compromising functional needs.

III. DESIGN PRINCIPLES

The same basic principles of design used for laboratory buildings can and should be used for vivaria, and the use of scale and proportion, sequence of space, light, and color apply equally. Laboratory architects use these principles in the design of interior lab, office and public spaces to provide interesting and visually attractive environments, and can use them equally in vivarium spaces.

A. Scale and Proportion

- *Vivarium entries*: the outermost staff entry is sometimes in a public space or corridor, and can be part of a graceful space even if disguised. An outer "cosmetic" door can conceal a vestibule with the secured-entry door inside; this will remove card readers, cameras and other items from public view, but still provide a sense of importance and design to people entering the vivarium. In a multi-storey building with a dedicated vivarium floor, the elevator lobby can be designed with the same scale and proportion as laboratory floors.
- *Interstitial floor benefits*: in addition to the technical advantages of using interstitial space above a vivarium, it creates very high floor-to-floor dimensions (in the range of 20–25 feet) that can permit higher ceilings in entries and non-animal spaces such as break areas;
- *Corridors*: long corridors can be modulated with varied lighting, floor patterns or wall colors in ways similar to laboratory design.
- *Interior glazing*: glass windows or lights in doors can make small spaces seem larger, in addition to the functional visibility that is often desirable.

B. Light

- *Natural light*: although housing areas typically cannot have exterior windows, many other spaces can. Procedure rooms are usually used during the daytime part of an animal's photoperiod, and can provide the humans with a view. If intrusion is possible, security glazing can be used, or windows can be small enough to prevent entry. Even frosted or fritted glass can provide daylight in locations where the vivarium must be disguised. For non-human primate spaces, appropriately placed exterior windows can add an important enrichment aspect; this is especially possible in multi-storey buildings with no risk of seeing into the rooms from the outside.
- *Artificial light*: areas other than housing and procedure space generally do not require specific color rendition for experimental purposes, and light fixtures can be arranged to provide varied levels and visual interest. Lamp types can be selected to provide warmth and comfort, and do not necessarily need to match lamps used in housing areas.
- *Interior glazing*: many areas of vivaria require visibility between rooms, whether for supervision or communication.

Adding interior windows and glazed door lights can provide a high degree of openness and spaciousness.

C. Color

- *Flooring*: the wide variety of matrix and chip colors available for resinous flooring provides great design flexibility, and even simple patterns or varied colors in different areas will improve the design. Sheet flooring also can be varied, with alternate colors seamed together or used in different areas.
- *Paint*: other than in housing and procedure areas with specific color rendition requirements, paint colors can be varied without limit.
- *Tiles*: in locker rooms, where ceramic tile is often used, patterns and variations can provide design interest.
- *Wood*: although wood is not suitable in most areas, break areas, locker rooms and offices can include wood casework and furniture, as long as the finish is a catalyzed polyurethane or similar washable coating.

IV. DESIGN FEATURES

The underground vivarium at Harvard University's Department of Molecular and Cellular Biology was completed in 2006 as an addition to an historic laboratory building at the Cambridge campus. Known as the Biological Resources Infrastructure (BRI) project, it includes 74,000 gross square feet of rodent barrier space constructed within an existing courtyard, and connected at the basement level. A combination of the limited land, historic context and a strong desire to maintain an active courtyard made an underground solution the best location, but presented the considerable challenge of providing humane space for the staff and investigators. Figure 11-1 illustrates the existing building context.

The vivarium entry includes provisions for people, materials and animals in three separate sequences of space, but which are connected to a single large entry point. The entry opens directly into the break area (Figure 11-2), which includes a skylight (Figure 11-3) up to the courtyard, and provides a welcoming appearance. Harvard also commissioned an art glass display (Figure 11-4) for the break area as an unusual recognition of the nature and importance of the work.

Staff and investigator entry into the barrier includes locker and shower space (Figure 11-5), as well as a gowning vestibule with a step-over bench and air showers (Figure 11-6). Each is designed to feature colorful materials, and the use of wood outside the barrier adds interest and visual comfort.

The main corridor (Figure 11-7) inside the barrier includes a supervisor's office with corner glazing and colorful walls. The corridor lighting pattern is varied and accented at each of the housing suite entries.

As a barrier facility, the BRI includes a transgenic core; this is located outside the barrier perimeter adjacent to a dedicated housing suite with pass-throughs (Figure 11-8). The core lab is designed as a "regular" laboratory space, with wood casework, comfortable lighting and varied finish colors.

Fig. 11-1 Molecular and Cellular Biology Building, Harvard University.

Fig. 11-2 Break area.

Fig. 11-3 Skylight.

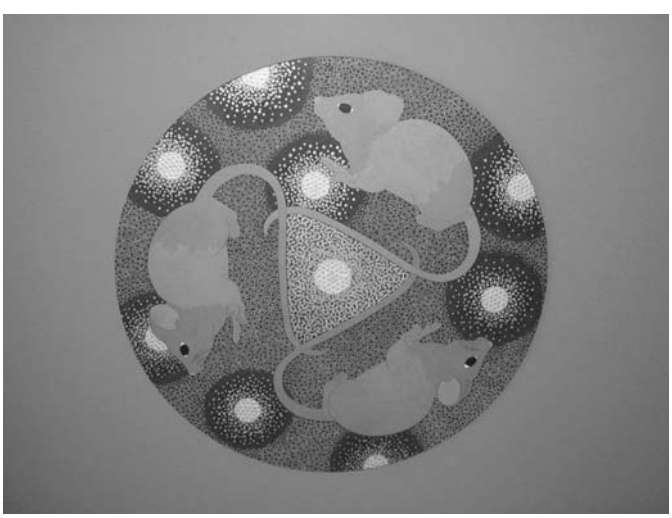

Fig. 11-4 Art glass.

The University of Massachusetts Medical School's Lazare Research Building was completed in 2001, and includes a 32,000 gross square foot vivarium operated as a rodent barrier. The building is a nine-storey research facility, with the main entry, cafeteria and vivarium located on the ground floor, and laboratories above. The building is sited on sloping land, with the vivarium concealed within the hill. The office portion of the vivarium is located on the downhill exterior wall, and has normal exterior windows. The vivarium entry (Figure 11-9) is located in the building's main lobby, which is unrestricted space during normal business hours to allow cafeteria access to the whole campus. The vivarium entry is disguised in a wood-paneled wall with no signage or locking; a vestibule behind the door provides a secured entry with full security features such as card readers and cameras.

Notes: Both the UMass and Harvard buildings were designed by Tsoi/Kobus & Associates, Inc. as architects, and lab/vivarium programming was provided by Jacobs Consultancy Inc./GPR Planners. Both authors of this chapter designed and programmed both projects.

All photographs within this chapter were taken by TK&A staff.

Fig. 11-5 Shower and locker area.

Fig. 11-6 Gowning air lock.

Fig. 11-7 Main corridor.

Fig. 11-8 Transgenic core laboratory.

Fig. 11-9 UMass Medical School Main Lobby and Vivarium Entry.

Chapter 12

Ergonomonic Considerations and Allergen Management

Michael J. Huerkamp, Michael A. Gladle, Michael P. Mottet and Kathy Forde

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I. INTRODUCTION

Occupational ergonomics ("ergonomics," "human engineering") is an applied science focused on the study of work, including the relationship of people to the work, the application of tools, and management of the physical work environment. Ergonomics as a term is derived from the Greek *ergo* meaning "work" and the ancient *nomos*, translated as "laws." In a practical sense, ergonomics is "a blinding flash of common sense backed by science" (Anonymous, 1996). The goal of the application of ergonomics is to maximize efficiency and safety in the workplace. It allows workers to operate at the limit of peak, safe performance by enabling the best fit of the job and arrangement of the environment to the person. In many cases, ergonomics allows for optimal task or process productivity above that achieved ordinarily in the work environment by removing or minimizing physical or process barriers, reducing motion waste and eliminating non-value-added tasks, and by preventing or reducing worker and task mismatches that lead to discomfort, fatigue, poor visual acuity, inefficiency and possible injury (Anonymous, 1996, 2003). As such, the minimization of worker exposure to sensitizing allergens in the physical work environment and the prevention of the distracting, energy-sapping or worse symptoms of laboratory animal allergy reasonably constitute a component of ergonomics. Organizations that enter proactively into the ergonomic process do so most prominently to reduce workers' compensation claims, enhance productivity/profitability, meet moral and ethical obligations to workers, and ablate the threat of increased regulation (Leard *et al.*, 1995; OSHA, 1999; Anonymous, 2003). In terms of regulatory oversight,

at the federal level and at least up through 2008, the emphasis appears to be upon non-compulsory voluntary workplace safety programs focusing on overuse injuries, and with the prospect of enforcement actions against negligent institutions having high injury rates (OSHA, 1999; Greenhouse, 2002) rather than formal regulation (OSHA, 1999).

In recent years in the Western workplace, musculoskeletal injuries from overexertion and repetition have increased in prevalence (Leard *et al*., 1995), although it is not clear whether this observation is due to an increased number of injuries, improvement in reporting, an increase in legal or compensatory activity on behalf of claimants due to heightened awareness, or a combination thereof. At any rate, in the United States these now account for at least one-third of all work-related injuries, and essentially the same proportion of workers' compensation expenses (OSHA, 1999; US Department of Labor, 2004). Lower-back injuries alone resulted in 16 percent of all workers' compensation claims and 33 percent of all claim costs in one study (Webster and Snook, 1994). Likewise, musculoskeletal injuries represent the most common form of work-associated injury in Great Britain and approximately 40 percent of those in Belgium (Anonymous, 2003). These maladies, known variously as ergonomic injuries, repetitive motion disorders, overuse injuries, cumulative trauma disorders or work-related musculoskeletal disorders (WMSDs), are caused by excessive and repeated physical microtrauma to the musculoskeletal system – predominately the hands, wrists, elbow, shoulders, neck and back. While repetition in and of itself is not physically harmful for workers, repetition combined with bad posture and/or force causes human–task physical mismatches and stress leading to complexities in completing tasks as well as eventual pain (Anonymous, 2003). Although impacted by lifestyle, physical attributes, and the difficulty scientifically to predict or measure (Leard *et al*., 1995), these also are manifested in the forms of reduced performance, absenteeism, poor morale, disability and job turnover (Anonymous, 2003). Additionally, workers with repetitive, otherwise harmless tasks can become fatigued at some point during the work day, with some risk of a corresponding decrease in job performance and increase in risk of injury due to inattention (Kristal-Boneh *et al*., 1996). Monotony, tedium and other aspects of the psychological work environment may even predispose a worker or employee to somatic illness (Linton and Kamwendo, 1989; Linton and Warg, 1993). Aside from the inefficiency brought on by malaise, the National Academy of Sciences recently conservatively estimated that 1,000,000 workers missed work and $45–54 billion were lost annually to WMSDs in the United States (Barondess *et al*., 2001). The estimated cost in 2003 for each low-back injury was $22,800 (Anonymous, 2003). According to the National Council on Compensation, employers pay approximately $30,000 per employee for direct medical expenses to treat a cumulative trauma disorder such as carpal tunnel syndrome, but lost productivity and legal fees resulting from worker compensation claims escalate that figure into the range of $100,000 (Hess, 1996). Most of these conditions and expenses are preventable and can be reduced through the use and application of proper ergonomic principles.

Laboratory animal allergy (LAA) is a common occupational hazard for personnel involved foremost in the care of research animals, but also in their study (Lutsky, 1987; Elliott *et al*., 2005; Pacheco, 2007). One in three animal workers is potentially at risk of LAA (Goodno and Stave, 2002). The condition may be developed with exposure to any of a broad range of densely housed species in the relatively confined spaces of the animal research facility (ARF), including most prominently mice, rats, guinea pigs, cats, rabbits, dogs, birds and even insects (Rees *et al*., 1998; Goodno and Stave, 2002). In the consideration of allergen exposure, the greatest risk activities are that of cage cleaning (Twiggs *et al*., 1982; Eggleston *et al*., 1989, 1990; Sakaguchi *et al*., 1989; Gordon *et al*., 1992), disposal of soiled litter (Gordon *et al*., 1992), changing of filters in animal rooms (Gordon and Preece, 2003), cage-washing procedures (Gordon and Preece, 2003) and direct handling of animals for research procedures such as surgery, blood collection, weighing, examination or euthanasia (Eggleston *et al*., 1989; Gordon and Preece, 2003). Jobs associated with lesser exposures to laboratory animal allergens include general cleaning activities in the ARF (e.g., floor mopping), indirect contact in animal rooms, and feeding animals (Gordon and Preece, 2003). Low animal-allergen exposure tasks include procedures with animal tissue, and handling unconscious or dead animals (Gordon and Preece, 2003). Independent of the work environment, the risk and ultimate development of LAA for any individual may vary depending upon that person's health and genetic background, lifestyle factors such as smoking and pet ownership, and other variables (Fuortes *et al*., 1996; Elliott *et al*., 2005). Personnel with pre-existing allergies or susceptibility have a substantially higher risk for LAA (Pacheco, 2007). Symptoms of LAA evolve slowly over the first few years of exposure (Bush and Stave, 2003). Without proper management of allergens, a range of 10–40 percent of persons working in the animal research facility may develop LAA (Fisher *et al*., 1998; Bush and Stave, 2003), with the most vulnerable group being animal-care technicians (Elliott *et al*., 2005). Many of the symptoms of LAA are irritating, distracting or fatiguing, and are expressed in the form of allergic rhinoconjunctivitis (sneezing, itchy eyes, runny noses) and contact hypersensitivity (skin rashes) (Pacheco, 2007) although, most seriously, about 10 percent of cases may culminate in asthma (Hunskaar and Fosse, 1993). Systemic treatment of symptomatic individuals add personal or institutional medical expense and, depending upon medication, can have annoying effects, impairing worker alertness and productivity (Berger, 1999) as well. Persons made sufficiently physically miserable through LAA hypersensitivity or imperiled by asthma will not only be less productive, but will also miss work (Bush and Stave, 2003) and often find that transfer to other jobs represents the only satisfactory means to obtain meaningful symptomatic

relief (Pacheco, 2007). The loss of highly qualified animal-care and scientific personnel will be to the detriment of the research animal-care and -use programs. The economic impact of LAA for individual research institutions and on a national scale can only be surmised, but must be substantial. From a total national cost of $7.3 billion in direct costs in 2002 for allergic rhinoconjunctivitis (Ray *et al*., 1999), the total cost to US employers for increased absenteeism and reduced productivity due to the full complement of allergies, of which LAA represents a subset, was almost $292 million (Schoenwetter *et al*., 2004). A study specific to LAA showed that over one-third of NIH animal workers were absent from work one or more times due to their symptoms (Bland *et al*., 1986). These findings mirror those from a study of 5,000 employees at 57 companies where 34 percent of employees with allergies said they missed 1–5 days of work per year as a direct result of allergy symptoms (Schoenwetter *et al*., 2004). The overall cost of absenteeism per employee for all causes and for any animal resources organization has been conservatively estimated to be in excess of $800 per year (Huerkamp, 2006a). Further, 82 percent of those with workplace-related allergies reported a 26 percent loss of effectiveness at work due to allergy symptoms where they were also affected an average of 69.9 days annually (Schoenwetter *et al*., 2004). While data for worker turnover caused by allergy are not known, it has been estimated that the replacement cost for an hourly employee in an animal resources operation may be $5,000 or more per vacancy (Schweitzer *et al*., 2003; Huerkamp, 2006b). These figures, loosely extrapolated to the 40,000–125,000 workers estimated to have research animal exposure in the United States (Seward, 1999), suggest a substantial LAA economic vulnerability for the animal research enterprise.

Animal research facilities are among the more complex and expensive projects to build and operate. It behooves that in both construction and operation, costs be conserved and performance enhanced. With emphasis on increasing quality, production, labor efficiency, cost-containment and safety, especially during times when the national workforce is declining in numbers, sound human engineering is perfectly suited as a fundamental precept for the design and operation of modern animal research facilities. This is especially pertinent for animal research enterprises of such size where an individual worker may manage or repetitively handle hundreds of rodent cages or potentially thousands of caging components per day. Few organizations providing animal-care services can afford the loss of talented technicians to preventable injury or nagging allergy, or to operate under concomitant untoward and costly conditions of high staff turnover. Given these circumstances, it is critical that the workplace be designed to maintain health and to facilitate what animal-care, as well as research, personnel do well and despite their weaknesses. People excel at decision-making, non-programmed activities, small force application, and teamwork (Anonymous, 1996). Compared to machines, people are not particularly adept at recurring tasks done at a high rate or large volume. As applied to the construction or renovation of animal research facilities, design should account for human physical capabilities and limitations in the workspaces, especially in relation to the tasks to be done there. Ergonomically correct floor planning, equipment purchase and installation, and provision of a ventilated, thermal and illuminated environment, accomplish this. Where allowed in the project budget, tools, non-fixed equipment and caging systems of sound ergonomic design should be acquired and provided.

Many meaningful advances in the animal research facility derived from ergonomics may be implemented in small and incremental ways through process adjustment, acquisition of new tools, re-engineering and infrequent revolutionary equipment upgrades. However, it is through facility construction and major renovation that momentous, enduring improvements can be achieved. Associated with a commitment to build, expand or renovate are often relatively high upfront costs that may cause alarm and be lamented by the administrative financial stewards and others in top management. However, in the long run, the effective application of ergonomics to facility design and renovation offers significant safety and long-term operational cost savings for the institution through enhancement of work efficiency and reduced employee downtime, illness, medical care, workman's compensation, and other associated costs (Hess, 1996). There are many components of ergonomics, including hazard identification and risk management, proper work and task mechanics, training and physical fitness of employees, selection of non-fixed equipment and hand tools, location and design of control panels and instrument displays, and engaged occupational medicine programs. The design facet of ergonomics largely involves the layout of physical space, the attributes and selection of fixed material-handling workstations, service access to utilities and fixtures, prospects for automation, and management of the physical environment. Task assessment as it relates to work with non-fixed pieces of equipment (e.g., isolators) and ergonomic risks related to the daily work routine (such as lifting and moving containers, reaching, cleaning animal rooms, handling small animals and their cages, and using small tools) are important ergonomic issues, but will not be largely considered herein. For a primer, the reader is referred to subject overviews of ergonomics by Chaffin *et al*. (1999), Humantech, Inc. (Anonymous, 1996, 2003) and Kerst (2003).

II. ERGONOMICS AND GENERAL FACILITY PLANNING

A significant challenge related to design is that often ergonomics enters the process as an afterthought, or not at all, leaving little opportunity for a significant and important impact upon final planning and even construction (Wulff *et al*., 1999a; Burns and Vicente, 2000). The ability to influence design decisions and make changes without high cost

implications is exponentially less during planning as compared to later stages. Even when appreciated, often other design, budget and scheduling considerations may take precedence over human engineering (Wulff *et al*., 1999a, 1999b). The reason architects and designers fail consistently to employ sound ergonomics seems to be a general lack of familiarity and sometimes perceptions of high cost (Wulff *et al*., 1999a, 1999b) in some combination with insufficient project budgets and scheduling complications. Given this predicament, and the general rule in design and construction being that it is more cost-effective to plan and implement upfront rather than to retrofit after the facility is finished, ergonomics, unless given attention during the design development phase, may be relegated to the sidelines (Wulff *et al*., 1999a).

Even where the project intent is to achieve a rational application of ergonomic principles in design, experience has shown that it is not sufficient to delineate the need for ergonomic applications in project documents (Wulff *et al*., 1999b). In Europe, for example, where ergonomics regulations and expectations with respect to design have existed since the late twentieth century, even regulatory pressure has been inconsistently influential in netting soundly designed projects (Wulff *et al*., 1999b). Instead, the increasing standards have contributed to a phenomenon of information overload and a reality where ergonomics criteria are not well known, understood or embraced among the project management team (Wulff *et al*., 1999b). Confounding even the well-intentioned is that ergonomics data are not easy to find (Wulff *et al*., 1999b) and are not necessarily easy to apply to the equipment and layout of animal research facilities. While it is admittedly a responsibility of the end-user to be likewise educated in the value of ergonomics applied to the care of research animals, and to be able to show it has a pay-off, given the specialized and sometimes compartmentalized nature of the knowledge this can be difficult and daunting. In some cases guidelines may take the form of a general formulation not easily adapted to a specific vivarium design situation, or may be so complex as to be difficult to understand or easily apply, for example the complicated and quite formulaic NIOSH lifting guide and calculation (NIOSH, 1981, 1988).

A tight budget and strict time limits may worsen the situation (Wulff *et al*., 1999a, 1999b), and there is an additional compounding risk in the case of naiveté and marginalization of the end-user (e.g., facility management and frontline technical staff) so that they cannot advocate for legitimate operational needs. Budgetary constraints can sometimes cause tension between the end-user, where the focus is on safety and low operating costs, and the administration and certain members of the project management team, whose objectives are low upfront costs, finishing under budget, and moving on to tackle the next project. These sorts of differences are not unnatural, however. Cost justification, the utilitarian weighing of the expenses and benefits of an initiative or perceived improvement, is a normal and customary business practice. It allows for optimal monetary investment, and uses dollars as the unit and basis of comparison. Consequently, when competing for the same allocation of money, the relative merit of ergonomic improvements must be subjected to the same intense scrutiny as all other potential applications. Unfortunately, health and safety cost savings, including those from ergonomics, while often substantial are difficult to track and tabulate (Anonymous, 2003). This makes them difficult to analyze, and correspondingly rationalize, in the context of a cost-justification exercise (Anonymous, 2003). Rather than focusing on indistinct economic incentives related to health benefits, the best course of action is to concentrate on the cost-effectiveness of enhanced productivity. This has proven to be the most straightforward means of cost-justifying ergonomic improvements, and can be measured down to the individual or workstation level (Anonymous, 2003).

With large projects, an additional consideration is that the parsing and distribution of work functionally among different members of the design team can be commonplace. This situation may, even with the best intentions to implement ergonomics, scatter personnel of varying expertise and sensitivity, and introduce dilution and inconsistency of effect (Wulff *et al*., 1999a, 1999b; Burns and Vicente, 2000). Additionally, design responsibilities may be distributed among persons or groups with different, perhaps even conflicting, goals or agendas (Wulff *et al*., 1999a; Burns and Vicente, 2000). The tragedy in this is that the facility end-user bears most fully the functional consequences of poor design, while the institution also pays in the form of lower productivity, increased workers' compensation costs, and potentially expensive modifications of the facility later.

Given this combination of daunting obstacles, success may not be easy to come by. For the design process to be one of quality, it must be made open to a full range of persons and entities, and particularly organized and orchestrated to promote a free exchange of legitimate interests in the best design (Wulff *et al*., 1999a). The leveraging of ergonomics into the design process often requires the combination of effective education and negotiation between all parties involved in the design and construction process, including the project planners, managers and financers. This happens most consistently and obviously where ergonomics specialists are engaged actively in facility design from the start (Wulff *et al*., 1999b), or at least where key and influential persons on the design team have some familiarity with ergonomics (Wulff *et al*., 1999a, 1999b). The former is a degreed, experienced and accredited or certified specialist with technical and professional expertise across the broad range of ergonomic subjects, including, most importantly, work, tool and workstation evaluation and advice, and injury prevention. Credentialing and the value of credentials is a potential concern in the rapidly growing field of ergonomics, where many practitioners may not have experience with research buildings, and inject a certain *caveat emptor* into

the hiring or selection of an ergonomic specialist. This makes the consideration of experience and professional or customer recommendations perhaps more important than the brand of a certain accreditation or certification. The other option, design team members with some ergonomic grounding, typically derives from one or more direct interactions with an ergonomist on another project or through other associations (Wulff *et al*., 1999a). Where the design team is perceived not to be ergonomic-savvy, and even in cases where there may be substantial knowledge of the field, it is often worthwhile for the team to avail itself of whatever specific local expertise is available. This may come in the form of persons affiliated with the institution and with some modicum of expertise in the areas of occupational medicine, environmental health and safety, or the Americans with Disabilities Act (ADA). It should be noted that the ADA document sets guidelines for accessibility to places of public accommodation and commercial facilities by individuals with disabilities; it does not provide guidance for ergonomic issues in facilities for individuals without disabilities. If used in the context of persons with disabilities, the use of ADA will be applicable and useful in facility design. There are also emerging software products that may enable architects to quantify a worker's biomechanical risk for injury based on a proposed workplace design (Feyen *et al*., 2006), although these are not well known at this time and are not accepted or used on a broad basis by designers currently. However, unlike architects, designers, medical and safety specialists and computer programs, qualified ergonomists are trained to translate and apply general guidelines to specific situations or approach unique scenarios in a scientific way so as to advance design (Wulff *et al*., 1999a). Given that the end-user, especially at a technical level, may not be represented adequately on the facility design team and not be in a position, or have the expertise, to express concerns, the ergonomic specialist importantly can function as a proxy representative for both those that will work in the facility as well as those that will manage it and those that will own it (Wulff *et al*., 1999a). This statement aside, some of the most fundamental and useful information in the consideration of design and its practical ramifications can be gleaned from technical staff involvement in the process (Hess, 1996).

III. LAYOUT OF PHYSICAL SPACE

Providing a safe and efficient workplace, while meeting other environmental control and containment/exclusion requirements, depends upon the creation of floor plans allowing for sensible circulation and sufficient space for the work (Rahija, 1999). This may require some element of *a priori* task analysis by the design team and facility management, as well as a consideration of the anthropometric attributes of the facility workforce and users (Burns and Vicente, 2000). The general ergonomic principles for interior design include short traverses to move heavy equipment, the presence of wide corridors (at least 7 feet, taking into consideration wall-protection rails and devices), a minimum of turns and corners for navigating the facility, no grade transitions or ramps, and ample space in support areas (Palkonen, 1993). The use of rails or other devices can result in a 6″ minimum loss of corridor width. Where a floor or corridor grade transition is required, the slope should be no steeper than 1 : 12.

In terms of specific architectural features, floors should be seamless and fairly smooth, but also slip and skid-proof, particularly in the wet environs of the facility (e.g., cage-wash, large animal housing rooms) in order to prevent falls and back or other injuries. It must be kept in mind that too much floor texture can result in difficulties in cleaning operations, which may increase the potential for injuries when mopping or using floor scrubbers. As such, the design team should specify a mock-up floor for acceptance by all parties prior to facility floor installation. Where possible, floors should allow for padding and shock absorption where personnel work standing and with relatively stationary postures. Doors with a width of 48 inches (rather than 42 inches) are better suited to the safe and easy movement of various types of materials in and out of rooms and storage areas (Rahija, 1999). The appropriateness of planned doorway height should likewise be evaluated, especially in scenarios where high-density rodent caging systems make increasing use of vertical capacity. Doors should be adequate in height and width to enable unwieldy transit of high-density caging systems, manual or programmable floor scrubbers, and other moveable items, without requiring dismantling of some or all of the equipment or with narrowness predisposing to crush and other traumas of the digits and hands. Wall-guard and door-jamb protection devices are effective in this regard. Entries into bulk feed and bedding storage areas in particular must be wide enough alone or in combination to accommodate the passage of a pallet (Figure 12-1). Automatic sliding doors are particularly useful in cage-wash and storage areas, where often individuals are moving carts or racks of materials to and fro (Figure 12-2). While motion sensors are often useful in combination, they should be used judiciously, especially in tight spaces where personnel traffic in front of the sensor may be commonplace. In facilities where there is likely to be considerable food preparation, diet kitchens should be designed with sufficient outlets (Ground Fault Interruption, GFI, if within 6′ of any water source), floor, counter and alcove space, and adjustable shelving to accommodate mixers and other equipment to automate and minimize the risk of cuts and musculoskeletal injuries (Rahija, 1999). Counters ordinarily are 36″ for standing-height work and 30″ tall where procedures will be performed seated. Autoclaves and washing equipment should be of sufficient capacity to easily manage the daily throughput with minimal handling by personnel, and used with compatible material handling carts to specifically eliminate needs for manual lifting and loading. Given that vehicles of a variety of heights and material off-loading capability may be involved in facility

Fig. 12-1 Dual door entry for a bulk feed and bedding storage area used to facilitate the passage of materials on pallets. The paired doors open inward and are each 84 inches high with one measuring 48 inches and the other 24 inches in width.
Photograph courtesy of Emory University, Atlanta, GA.

Fig. 12-2 Automatic sliding doors for high traverse areas such as cage-wash (pictured), docks or other sites with high pedestrian or moveable equipment traffic.
Photograph courtesy of Emory University, Atlanta, GA.

pick-ups and deliveries, docks should be installed with hydraulic lifts to facilitate these processes (Figure 12-3). Likewise, the pavement for vehicle parking at the dock should be level and incline-free to minimize the forces necessary to push and pull loads back and forth between trucks and the loading dock. Docks should also be of sufficient width and bay capacity to allow for efficient access by delivery, pick-up and other vehicles supporting the enterprise.

Fig. 12-3 Loading dock with dual hydraulic lifts allowing for more than one vehicle to access the dock simultaneously.
Photograph courtesy of Emory University, Atlanta, GA.

Storage areas and workplaces where working quantities of materials are kept merit special ergonomic consideration. Due to the demand for economical use of space and the perception that space allocated for storage can frequently be used for better and more efficient purposes, it is often given short shrift. This may create a relative lack of space in the facility, typically devolving to elevated solutions requiring some equipment and supplies to be stored on overhead shelves. This is a risk factor for ergonomically-related disorders such as back, neck and shoulder strain and thoracic outlet syndrome. Where overhead lifting must be done in the animal research facility, such as in the cage-wash resource, procedure rooms, laboratories, necropsy and storage areas, several fundamentals should be applied in design. First, shelving should be adjustable. Plans must consider that heavy objects will be kept on shelves below shoulder height whenever possible. Materials that are infrequently used and lightweight can be kept on shelving units which are located higher than shoulder height. Additionally, task-work spaces should be designed to prevent twisting while lifting or working. Task design, including the lifting of objects, should allow for the work to be accomplished directly in front of the worker. Facility management, after taking possession of the facility, can follow on with sensible, low-cost and non-fixed ergonomic solutions, such as providing stable footstools or step-ladders to enable access to objects stored on shelves. Rotating carousels can be employed at certain workstations to bring materials close to the worker and reduce excessive twisting or reaching for objects. In storage areas, especially those where bags of food or bedding are stacked or palletized, adjustable (scissors) dunnage racks (Figure 12-4) allow for the loading and unloading surface to be adjusted as needed to a safe working height. Hoist and overhead rail systems installed during construction permit the lifting from pallets and conveyance of bulk bags of

Fig. 12-4 Adjustable (scissors) dunnage rack allows for the loading and unloading surface to be adjusted as needed to the safe height for any worker.
Photograph courtesy of Emory University, Atlanta, GA.

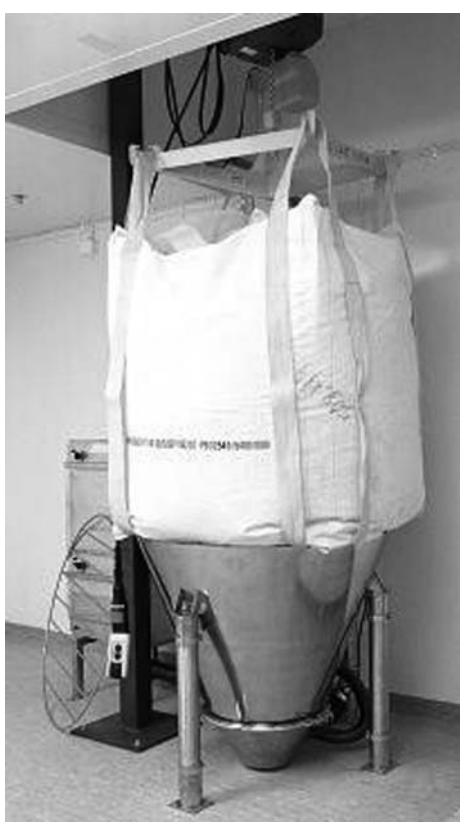

Fig. 12-5 Overhead emptying of a bulk bag of contact bedding into a bedding system load funnel enabled by a hoist and rail overhead system.
Photograph courtesy of Detach AB, Strängnäs, Sweden.

contact bedding, weighing up to 1,000 pounds each, from storage to the bedding loading area (Figure 12-5). Dispensing bedding into funnel devices or storage containers via an overhead pour spares personnel from otherwise handling, opening and unloading the equivalent of 40–50 paper bags, and simplifies and expedites the bedding handling process. Where construction plans do not allow for sufficient overhead clearance, where an overhead system would simply be undesirable, or where installation may not be possible through renovation, automated bag openers and compact bedding vacuum systems are an alternative to the hoist and overhead conveyor system enabling bulk bag evacuation and bedding system loading while reducing labor expenses and worker exposure to dust and allergens.

Ergonomic applications related to plumbing include the installation of reliable self-priming trap drains, where feasible, to eliminate the time and risky stooping postures involved in the regular manual dumping of water into drains. It should be noted that self-priming traps require a water source in close proximity and may not be applicable in all work locations, such as in the middle of a room distant from any sink or other water source. Where a single user may use a sink at high frequency, such as in cage-wash, the faucet should ideally be hands-free and foot- or paddle-operated. In aquatic, large animal housing areas, and cage-wash areas where hoses are used, lightweight hoses and ergonomically correct spray nozzles, such as those with swivel heads or locking spray actuators, can prevent injury.

Product and systems designers do not necessarily create materials or configurations according to ergonomic principles. Although not uncommonly overlooked, the selection and installation of simple appurtenances can have a profound ergonomic effect upon the maintenance of a facility. For example, choosing light fixture, vented duct covers and paper-towel dispensers that are accessed using simple latches, rather than screws or nuts and bolts, can offer efficiency and safety. With filter grille covers particularly, permanently attached latches are less likely to become lost or misplaced as compared to screws facilitating consistent proper alignment and closure of the grille cover. From a service perspective, it also takes less time to disengage a latch or two, while eliminating repeated movements, done at a high rate, and often involving abnormal postures and more than minimal force, that predispose to WMSDs. For example, imagine the time, awkward postures and repetitive motion associated with removing a series of screws from a ceiling light fixture while standing upon a ladder and with arms extended overhead as compared to disengaging a couple of latches. Likewise, paper-towel dispensers should be secured with latches rather than keys that can become misplaced, lost or obsolete and difficult to replace.

IV. FIXED MATERIAL HANDLING WORKSTATIONS

Workplaces and workstations are not always designed to promote worker's health and production efficiency. While it is important to appreciate that no perfect workstation exists

for the most part, it is critical to aspire to design and implement to the elusive goal of perfection in workstations. Fixed workstations in the animal research facility can be found most commonly in the cage-washing resource and most frequently in the form of sinks, automatic feed and bedding disposal units, tunnel washer loading and discharge platforms, and water bottle-filling devices. In rodent housing rooms, and especially small animal biocontainment areas, stationary biological safety cabinets (BSC) are the most commonly encountered fixed workstations. Mobile cage transfer stations may also be found, but are typically owner-furnished at about the time of building occupancy. Workstations may also be found in research procedure rooms where casework counter surfaces may be dedicated as fixed spaces for surgery, necropsy or other research or diagnostic procedures. Fixed or adjustable height backdraft and downdraft necropsy tables are additional examples of fixed workstations that may be designed into facilities. Dumpsters are an often unrecognized workstation, but if soiled bedding is disposed in a dumpster by manual methods (e.g., hauling or lifting), the design/transportation of the waste bin and the configuration of the bulk receptacle should be ergonomically appropriate.

An ergonomically sound workstation optimizes the performance of any individual operation within the context of the overall material or animal handling and processing system (Anonymous, 2003). As such, workplaces must be designed to meet material-handling process requirements while ostensibly remaining within the realm of human capability (Anonymous, 2003). As applied to facility design, rather than inventing new workstations, ergonomic design guidelines take human performance and task attributes and translate them into equipment applicability and procurement specifications (Anonymous, 2003). Keeping in mind that manufacturers do not necessarily create goods meeting ergonomic principles, an informed buying perspective is critical. The workstations installed in animal research facilities may present ergonomic hazards mostly due to overly expansive work areas requiring excessive reaches along with the lack of height adjustability and sufficient leg room.

From an ergonomic design standpoint, the optimal application is to use criteria that are based upon physical traits and capabilities of the user population. These can vary from continent to continent. Whenever possible, a range of adjustability should be provided so as to reasonably accommodate the anthropometric extremes (e.g., range from 5th percentile female to 95th percentile male) (Anonymous, 2003). In general, workstation surfaces for light work in North America, such as rodent cage handling or processing, should be located 33″–42″ from the floor and ideally be adjustable within that range (Anonymous, 2003). For continuous work, particularly when handling materials weighing more than 10 pounds, the work surface should be adjustable between 28 and 39 inches (Anonymous, 2003). If the surface must be of fixed and permanent height, it is most sensible to locate it at the high extreme and accommodate shorter persons by using risers or platforms. The most effective and safest work surface for a standing workstation allows for the activity to be contained within a 40″ width, and requiring no more than a 18″ reach or rotation of no more than12″–17″ from the center (Leard *et al*., 1995; Anonymous, 1996, 2003).

To minimize ergonomic hazards associated with their use, BSC should be selected with design features that include perforated front grills of minimum effective depth that allow for the front edge of the solid work surface to be located closer to the worker. Height adjustability, by hand-crank or hydraulic lift (Figure 12-6), allows for safe postures to be used by a range of members of a workforce with a diversity of heights. Mobile cage transfer stations offer the advantage of typically being height adjustable, whereas most BSC are not always so and sometimes require retrospective modification. It also bears mention that BSC that are hard-ducted to utilities or with fixed exhaust connections typically are not adjustable. Analysis shows that less force and effort is needed to push or pull a mobile hood to a stationary rack (6–31 pounds push or 17–29 pounds pull) than to move a fully loaded rodent rack (84 cages) to a stationary BSC (10–45 pounds push or 18–48 pounds pull) (K. Forde, personal communication). Although it may not be possible for BSC or other applications in the facility, non-glare glass on the sash window and/or adjustable plexiglass barriers enhance visual ergonomics. During the commissioning and validation phase, the end-user should be advised to consult with institutional occupational health experts to evaluate if closed-cell foam padding applied to the front edge of the BSC has value. Such material should withstand decontamination procedures and be located away from the downdraft at the front sash so as not to alter airflow. Alternatively, for those seated and doing repetitive and focused work, factory-applied movable armrests may be installed external to the cabinet or edge of the workbench to provide support for the arms of sitting individuals while not compromising the required airflow. These improvements reduce contact forces by increasing the surface area that comes into contact with the forearm, thus minimizing the chances of impinging nerves, tendons, or blood vessels. Other considerations for workstations are to provide footrests and to allow for the use of durable, sanitizable anti-fatigue matting compatible with the environment of animal research facility for personnel who must stand for extended periods of time. Rather than anti-fatigue matting, which may be cumbersome in some circumstances – especially if personnel are not confined to a small work area – facility management can provide staff with slip-resistant, cushioned insole, polyurethane clogs or viscole shoe inserts. If included in the project budget, chairs for BSC and procedure-room work benches should be ergonomically designed, meeting the requirements for adequate back support, adjustable seat angle, seat depth, seat and arm-rest width (if needed), and sufficient seat and arm-rest height adjustability. Chairs should be equipped with footrests or adjustable height ring stands for individuals whose feet do not rest comfortably on the floor. Facility end-users should be instructed in proper use and adjustment of the chair, and advised to keep the space under

Fig. 12-6 Stationary biosafety cabinet (left) and mobile cage-changing station (right) featuring front grills of minimal depth to decrease reaching and stretching to areas of the work surface and height adjustability by hand-crank (arrows). Automated hydraulic lifts are an option instead of manual cranks. These features allow for safe postures and reaches to be used by a range of workers of varying height and size.

Photograph courtesy of Emory University, Atlanta, GA.

the work surface free of drawers, storage carts, supplies, refrigerators and the like to provide leg room. Turntables can be used to store equipment and supplies within reasonable proximity of workers. These refinements will reduce excessive reaching and twisting, and prevent increased loads on the low back.

V. ALLERGEN MANAGEMENT

The principle of dilution and room air turnover rates, used with great success for heat, odor and airborne microorganism management, have not been shown to be effective in the removal or dilution of submicron aeroallergens except at energy-intensive fresh air exchange rates exceeding 100 air changes per hour (Swanson *et al*., 1990; Wood *et al*., 1993). Instead of this approach, and to the good fortune of construction project budgets, growing evidence reinforces that the purchase of rodent caging and equipment and, to a lesser extent, cutting-edge facility design, effectively minimize allergens in the ARF environment and correspondingly favorably influence the frequency of LAA sensitization (Harrison, 2001). In the overall management of allergens in the ARF, facility design, engineering controls and equipment integration are only part of a multifaceted program that also must include administrative programs, medical surveillance, the use of personal protective equipment (PPE) appropriate to the risk and task, and training in allergen awareness, proper equipment use and other means to reduce exposure and prevent contamination (Fisher *et al*., 1998; Harrison, 2001). Mice and rats are far and away the most popular mammals in research and, likewise, the primary causative species for LAA (Goodno and Stave, 2002). Multiple studies conducted by both qualified allergists and animal resources program teams demonstrate that the use of filter top cages (Sakaguchi *et al*., 1990; Harrison, 2001; Gordon and Preece, 2003), ventilated caging systems with negative differential air pressure between the cage and macroenvironment (Gordon *et al*., 2001; Harrison, 2001; Thulin *et al*., 2002; Gordon and Preece, 2003; Schweitzer *et al*., 2003), the treatment of cage exhaust by HEPA filtration (Ziemann *et al*., 1992; Platts-Mills *et al*., 2005), the manipulation of animals and opened cages in downdraft or backdraft ventilated hoods and workstations (Reeb-Whitaker *et al*., 1999; Harrison, 2001; Thulin *et al*., 2002; Schweitzer *et al*., 2003), and the deployment of cage-waste dumping stations (Harrison, 2001; Thulin *et al*., 2002) and removal of soiled bedding by vacuum rather than dumping (Gordon *et al*., 2001) minimize worker exposure to allergens from these species. Going a step beyond these task-specific local ventilation management interventions, ventilation-system design that enables the ducting of the

Fig. 12-7 Mouse individually ventilated cage effluent ducted to the building exhaust (white arrow) through a transition device/damper mechanism (black arrow).

Photograph courtesy of Emory University.

cage/rack exhaust directly into the building discharge system (instead of back into the room) will favorably influence energy consumption in the operation of the facility (due to animal and motor heat removal), rack purchase cost (as an exhaust blower will not be needed) and animal odor elimination, and will possibly further contribute to allergen minimization (Figure 12-7). Other important considerations impacting allergen management are ARF design and operation fundamentals that include "single pass" air-handling systems, negative differential airflow for animal housing rooms, ventilating the animal housing and procedure rooms separately from laboratory and office spaces, and providing surfaces that can be readily washed down. Because contamination of clothing can be an important means of disseminating allergens, endotoxins and animal microbial flora from beyond the confines of the ARF, and represent an important means of exposing workers without direct animal contact, the public and family members to sensitizing inoculi (Harrison, 2001; Bush and Stave, 2003; Gordon and Preece, 2003), the dedication of outer garments (e.g., laboratory coats) for animal handing in the ARF is critical. Consequently, design should account for locker-room capacity sufficient to store personal effects and to allow for clothing changes where needed, gown and laboratory coat hooks adjacent to animal housing rooms, PPE storage and ready access, and stations for the storing and charging of battery-powered, air-purifying, full-face respirators.

VI. AUTOMATION

A key, but expensive, aspect of ergonomics is in the sensible application of automation to animal care. This technology, well-established in medical technology (Sarkozi *et al*., 2003) and extensively in manufacturing, is only emerging in animal resources. Keeping in mind that machines are most suitable for pre-programmed activities, high throughput repetition, applying ballistic forces, working in hazardous areas and process consistency (Anonymous, 1996), the opportunities for automation in the animal research facility are numerous. Current applications include soiled contact bedding disposal, clean contact bedding dispensation, cage and water bottle washing (including capping and uncapping), animal drinking water supply, and feed delivery. Automation in these cases may reduce stress, eliminates many potential injuries and disorders associated with the overuse of muscles, bad posture and repeated tasks, reduces the risk of inefficiency or injury from inattentiveness brought on by the boredom of repetitive tasks, and contains allergens (Harrison, 2001). It allows for human resources to be allocated to animal-care and science support activities rather than assigned to the monotonous repetition of inanimate material handling processes.

From an ergonomic perspective, handling large volumes of rodent cages, water bottles and accessories can be a highly repetitive activity. When engaged in such work, there is the risk for a combination of bad postures occurring at an excessive frequency and sometimes involving considerable force, predisposing to regular microtrauma and subsequent musculoskeletal injury. For example, in the dumping of soiled bedding and inverting solid-bottom rodent cages onto the conveyor of a tunnel washer, finger pinch grips and presses, radial (lateral) and ulnar (medial) deviations at the wrist, inward rotation and full extension of the forearm, and twisting at the waist – all inappropriate postures or movements – may occur at excessive frequency and predispose employees to a number of injuries, including carpal tunnel syndrome, ganglion cysts, wrist/elbow tendonitis and back strain (Anonymous, 1996). The handling of water bottles has been ranked as one of the most high-risk procedures for WMSDs, followed by various scenarios of handling rodent cages (Georgelos *et al*., 1999).

The most dramatic and innovative application of ergonomics to animal research facility operations has been in cage-washing. The range of options for cage-washing begins with washing by hand and extends all the way to all-in and all-out robotic handling of rodent cages and water bottles (Figure 12-8). Even

Fig. 12-8 Robotic cage-washing system showing both the soiled-side robot (left) and clean-side counterpart (right). The soiled side also shows the dirty bedding dumping station (D), in conveyor track (I) and first tunnel washer section (T). On the clean side are bedding cages on the out conveyor (O), automated bedding dispenser (B) and egress section of the tunnel washer (T).

Photograph courtesy of Emory University, Atlanta, GA.

the hazard for WMSD presented by the water bottle uncapping and capping process can be automated. Despite such impressive applications, however, it is important to remain mindful that automation itself may introduce the novel risk of injury where none existed before (NIOSH, 1988) – for example, persons working with robots are at risk of being struck by arms programmed to move regularly and not capable of sensing a human obstruction. As such, any staff member involved in the automation area must be educated on equipment performance and safety procedures to avoid such instances and injuries.

VII. PHYSICAL ENVIRONMENT

Adequate control of temperature, relative humidity, light, noise and vibration in the work environment is important to optimize efficiency and prevent discomfort, fatigue, distraction and/or injury (Anonymous, 1996). There can be interactions between various environmental components with increasing deleterious effect (Pellerin and Candas, 2004). Cold thermal environments are not likely to be encountered in the animal research facility, except perhaps in special facilities for amphibian housing or torpor/hibernation induction. However, hot and humid conditions may be commonplace and can be especially taxing, mentally draining and distracting (Anonymous, 1996; Kristal-Boneh *et al*., 1996). Steamy conditions may be found in cage-wash areas, around autoclaves and in large animal housing rooms, especially where sanitation involves the spraying of hot water. Additionally, although not typically the case with new construction, risks may abound in rodent housing rooms in older facilities, where the HVAC system may not be sufficient to manage the heat generated by the combination of lights, animals, caging system blower motors, humans and the use of mechanical equipment such as BSC or mobile cage-change stations. Add to that the prospect of workers garbed in protective apparel, possibly including devices that increase the work of breathing (such as N-95 respirators) or add extra weight (such as purifying air-powered respirators, PAPR), and the prospects for heat stress and fatigue are amplified.

The optimal temperature range for the working environment involving moderately active work, typical of most duties in the animal research facility, is 18–23°C (64–73°F) (Anonymous, 1996). Fortunately, this range falls conveniently within the *Guide* allowance for most species, particularly rodents (ILAR, 1996), and can be achieved without special accommodation. The relative humidity comfort range for work by humans allows greater latitude than the *Guide*, ranging from 20 percent to 70 percent (Anonymous, 1996), but again easily achievable within the animal research facility.

Inadequate illumination can lead to poor posturing, eye strain, headaches and corresponding decreases in productivity (Anonymous, 1996). Animal housing rooms designed for dual lighting levels meeting *Guide* standards provide for adequate human visual acuity. Humans engaged in work involving visual tasks of medium contrast or small size, such as handling, observing or examining mice or reading cage cards, for example, require a minimum of 46 foot-candles and a maximum of 93 foot-candles at the work surface (Anonymous, 1996). This can be met where the general lighting system allows for 30–35 foot-candles measured 1 meter from the floor (ILAR, 1996) and with an override capability to boost to 70 foot-candles for personnel working in the room. Alternatively, adequate illumination at the work surface, such as when servicing rodent cages, can be accomplished using the local task-lighting

found on BSC, mobile workstations and the like. Lighting should not be projected so as to cause glare and, as covered previously, light fixtures should be easy to clean and maintain.

In addition to fatiguing heat and humidity, noise in excess may be a risk in some areas of the animal facility, most notably cage-wash, but also in housing rooms where the clamor of swine, dogs or non-human primates may be extreme. A loud auditory environment may cause communication interference, annoyance, physical distress and hearing loss (Anonymous, 1996), and may exacerbate the unpleasantness and cognitive decline associated with thermal conditions (Pellerin and Candas, 2004). Decreases in productivity have also been observed when noise may be variable in level or content, or intermittent, high-level and repetitive (Anonymous, 1996). For human workers, it is recommended that ambient noise levels should be at or below 80 dB (Anonymous, 1996). This acoustical environment is also compatible with research needs (ILAR, 1996), although it is possible in certain circumstances that quieter conditions would be optimal. Where noises generated by equipment, animals or human work or traffic have the potential to be excessive and continuous or intermittent, noise abatement interventions should be utilized (Anonymous, 1996). These improvements may include baffles, sound-attenuating panels, gaskets on doors, intermediate door placement in corridors, and the like. In the operation of equipment, engineering controls should be implemented so that noise levels do not exceed 85 dB at a distance of more than 3 feet from operating equipment (Anonymous, 1996).

Exposure to vibration, whether whole-body or focal, is not a typical risk in the care of research animals. Such exposure might be possible through driving, operating forklifts, using pressurized washers or hoses, grinding waste, or working with hand tools. For vibration to induce pathologic effects, it must meet certain conditions of frequency, acceleration, direction and duration (Anonymous, 1996). High-frequency whole-body vibration (>2 Hz) may cause losses in precision manipulation and visual acuity, fatigue, or more severe effects (Anonymous, 1996). Focal or segmental vibration, usually associated with the operation of hand tools, may result in circulatory disturbances of the hand and wrist, manifested in the form of numbness, loss of dexterity and other conditions (Anonymous, 1996).

VIII. CONCLUSION

If people are the sole source of productivity and innovation and there can be no progress in these regards without safety, then ergonomics adopted and applied during times of facility construction and renovation offers the opportunity for momentous changes in productivity and worker safety. Because decisions made at the beginning of the design project can profoundly influence what solutions are feasible (if any) by the end of the project, the embracing of ergonomics in facility design requires an early commitment and interdisciplinary appreciation and desire on the part of the project management team, senior leadership and end-user. In doing so, the project management team should objectively weigh the needs of the financial and end-user stakeholders and, where indicated, go beyond rote design to invest in ergonomic applications that demonstrate a benefit for both. This may require that the end-users develop some modicum of ergonomics expertise themselves so as to be able to show that ergonomics applied to the care of research animals works and has a pay-off. However, experience has shown that this may only be best and consistently achieved, even in the face of institutional expectation or some degree of regulatory pressure, through the rational participation of qualified ergonomists.

In the end, however, more studies are needed that demonstrate that the economic benefits to be realized specifically in the animal research facility are real and more than conceptual. This means showing that the value of the investment in any ergonomic innovation more than pays for itself in terms of dollars saved through enhanced performance, improved attendance, high staff retention, lowered rates of injury and disability, and diminished workmens' compensation claims. As designers and animal research facility users and management develop more knowledge and appreciation of ergonomics, more refined solutions and suitable applications will be stimulated or will become apparent. If we are challenged to go beyond the traditional and into the realm of what ordinarily would not be done, who knows where the future lies? Will it be one where more highly integrated work teams are facilitated by individual wireless communications technology applications, electrically-powered assist machines, or even mobile robots programmed to deliver and pick up material from rooms? Those of us that use and design animal research resources will be limited only by our knowledge and imagination regarding what can be possible at the convergence of safety, productivity and economy.

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Chapter 13

Interstitial Mechanical Space

Steven L. Leary and Josh S. Meyer

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I. BACKGROUND

In traditional construction, mechanical space is placed above the ceiling. This method requires that maintenance and service personnel access the space from inside the laboratory or animal housing room (Figure 13-1).

Interstitial space is the architectural term for full-height, unoccupied mechanical and/or maintenance space between occupied floors. This method allows access by maintenance and service personnel without disrupting laboratory operations or animal housing areas.

As a general rule, facility design is not a one-size-fits-all proposition, and the incorporation of interstitial space does raise certain issues that should be fully explored and addressed to ascertain whether its inclusion is the right course.

II. TYPES OF INTERSTITIAL SPACE

Full interstitial space is an additional, unoccupied, full-height, fully walkable floor housing all mechanical equipment and systems for laboratories on the floor below (or sometimes both below and above). Full interstitial space is typically placed above an occupied lab floor with a 9′–10′ (nominal) ceiling (Figure 13-2).

Partial interstitial space is a level (not a complete floor) atop a portion of occupied laboratory or housing floors. This otherwise unoccupied level contains mechanical equipment and is accessed by walkways (Figure 13-3). The space over the equipment may have a nominal ceiling, but the portion that covers laboratories or housing space may accommodate a higher ceiling.

A *catwalk system* is the placement of a catwalk over a small portion of the occupied floor, usually the corridor (Figures 13-4, 13-5).

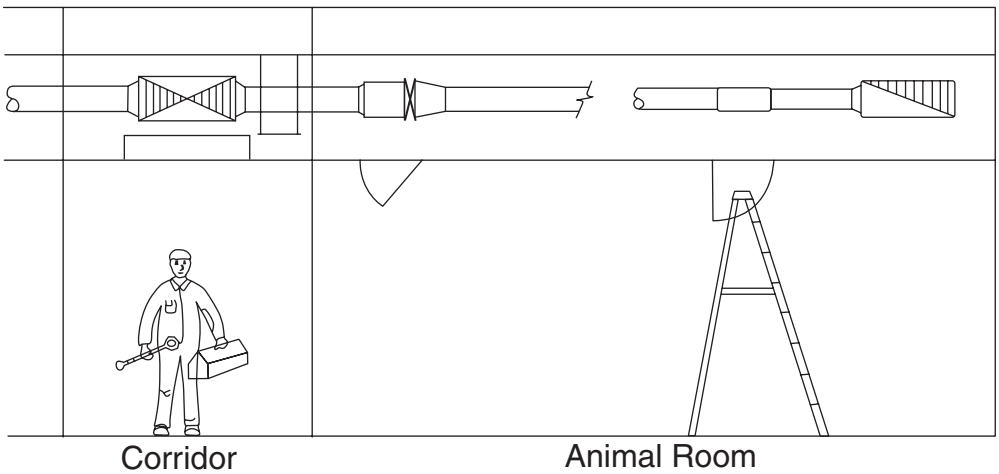

Fig. 13-1 Traditional construction with mechanical space above ceiling, requiring access by maintenance staff.
Reproduced with permission from Affiliated Engineers, Incorporated (AEI).

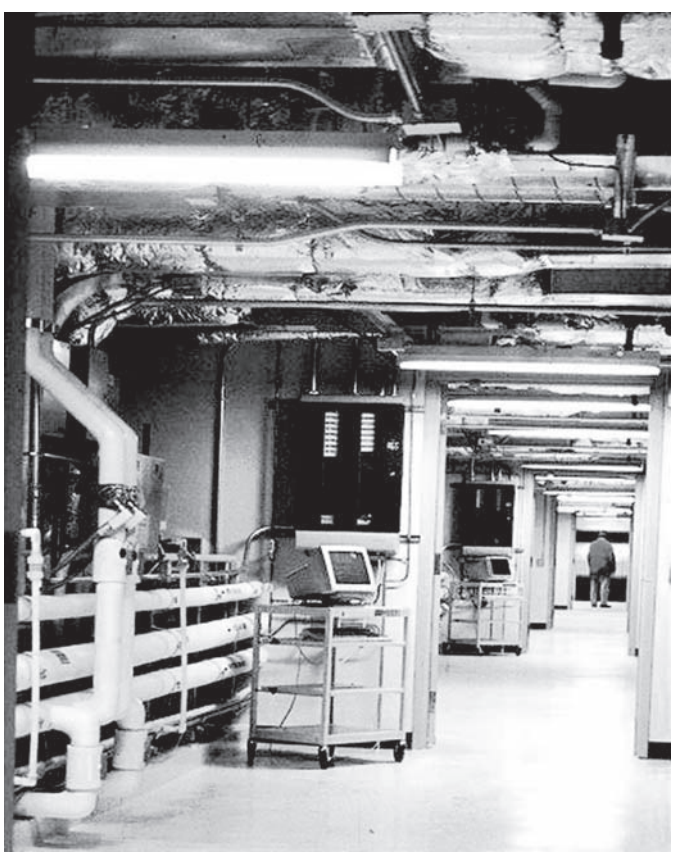

Fig. 13-2 Example of full interstitial space with walkable floor (Confidential client).

Fig. 13-3 Example of partial interstitial space with walkways (Washington University School of Medicine, St Louis, Missouri).

III. WEIGHING THE OPTIONS

The incorporation of interstitial space into new construction offers significant advantages to traditional construction when used in laboratory and animal housing facilities. However, there are also significant disadvantages, and these must be carefully considered and fully understood during the early facility planning and design phases.

A. Advantages

The most significant advantage provided by the use of interstitial space is flexibility: investigators may reconfigure laboratories as their research changes, adding equipment and processes, and accessing different types of gases and electricity; animal housing may grow and change depending on the species being housed, service and maintenance personnel may work on laboratory systems without interrupting or hindering researchers, administrators and building managers may renovate

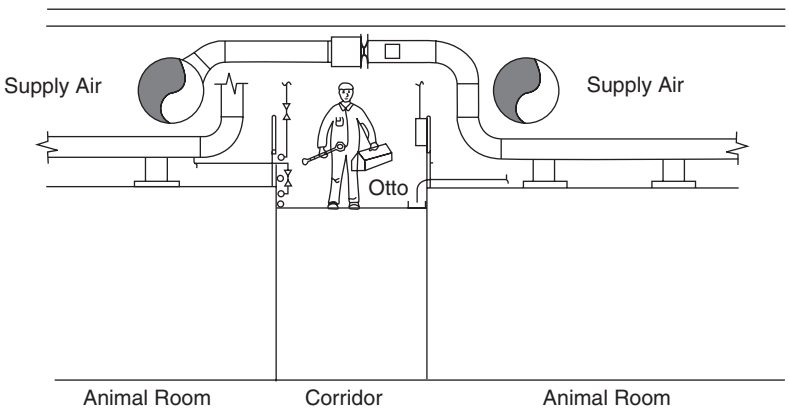

Fig. 13-4 Schematic of catwalk system over corridor. Reproduced with permission from Affiliated Engineers, Incorporated (AEI).

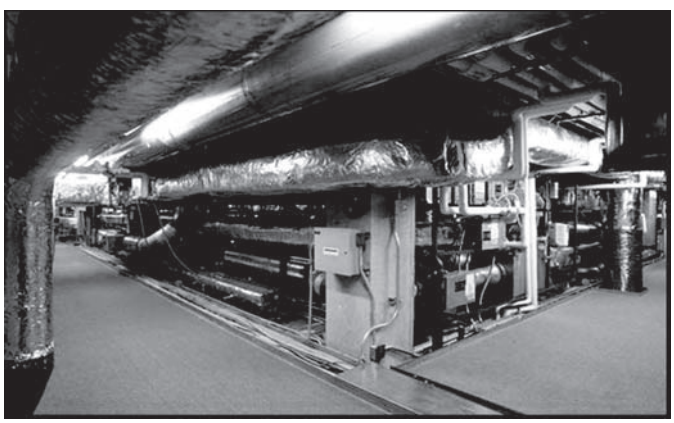

Fig. 13-5 Example of a catwalk system (Transgenic Mouse Facility, Baylor College of Medicine, Houston, Texas).

a single laboratory or animal housing area without disrupting the entire facility. Additional advantages are accessibility, esthetics/ergonomics, labor and construction time savings, and efficiency over the lifecycle of the building.

1. *Flexibility*

The flexibility of having all services and maintenance outside the laboratory block is invaluable. This is especially true of complex laboratory functions in which the work is sensitive (e.g., BSL3 applications, core labs or vivaria) or requires extremely clean conditions (e.g., formulation labs, clean rooms and barrier animal housing facilities). In addition, bench reconfiguration within the laboratory is facilitated by the absence of plumbing connections running through horizontal service chases (Higginbottom, 2001).

Interstitial floors may also contribute to structural flexibility when constructed as a system of trusses within the interstitial floor that holds up the ceiling for the lab floor below and supports the floor in the labs above, eliminating load-bearing walls on the lab floors. Laboratories can be configured and reconfigured as the research demands.

2. *Accessibility*

Service personnel are often anxious about entering a laboratory environment, particularly in BSL laboratories, where potentially dangerous diseases are the basis of research. By maintaining equipment in full interstitial space, service workers and engineers never have to enter a laboratory or animal housing area. They may access equipment on their own schedule, with minimal disruption to research activity. Even partial interstitial space can provide full access without entering laboratory space via an interstitial access corridor to VAV supply and exhaust boxes, including coils and controls.

Utilizing a catwalk system, services are delivered to laboratories from above via an overhead service carrier or "umbilical" in the laboratory. Some casework manufacturers design a system that includes utility drop poles as part of the casework strut system, offering another option for providing services from overhead.

3. *Esthetics*

With increasing emphasis on ergonomic workspaces, natural light has become a key design issue, and the exterior of the building is affected by the use of interstitial space. Therefore, the design team needs to consider carefully the window design and the exterior glass pattern early in the planning process.

For example, partial interstitial space located on the interior of the floor plate and stopping at the end of the lab benches allows for a higher ceiling in the lab from that point to the building perimeter. This in turn allows for placement of research workstations at the perimeter of the lab near very large windows, so natural light reaches the laboratory benches.

4. *Reduced Construction Time*

During construction, the use of interstitial space (as opposed to traditional service areas) results in ease of coordination between trades, shorter construction periods, and lower rates. Tradespersons work from the floor rather than on ladders and scaffolds, reducing safety concerns and "territorial"

issues. Additionally, work on the interstitial floor may be concurrent with work on laboratory floors, easing the construction sequence.

5. *Operating and Lifecycle Costs*

Interstitial space can lower lifecycle costs for the facility. When a facility is reconfigured frequently and/or frequent renovation and maintenance are required, then mechanical, electrical and plumbing systems work in interstitial space rather than in the laboratory results in less downtime. Researchers state unequivocally that as little downtime as possible is mission-critical to them.

Additionally, when routine service and maintenance need not interrupt laboratory activity, service engineers can be responsible for more area. In one major US cancer research center, operating engineers are responsible for 40 percent more building area than at comparable institutions (US Environmental Protection Agency, 2001).

B. Disadvantages

The most significant disadvantage is expense: interstitial space increases the initial cost of the building, increasing gross square footage and floor-to-floor height (16–18 feet partial or 18–20 feet full vs 15–16 feet traditional) and thereby affecting local zoning and building codes. Also affected are structural system requirements, fire protection systems, elevators and stairs. Moreover, including interstitial space in calculations of gross square footage will result in a building which, on paper, appears to be inefficient.

1. *Expense*

Obviously, these are only examples, and individual project costs will depend on the type of facility being built, but they do illustrate the expense consideration of interstitial space versus traditional construction.

In one recent two-storey facility, the additional cost of partial interstitial space was $6.80/gsf. However, in another recent two-storey animal housing facility project, partial interstitial space added $10.80/gsf, or 3.2 percent. A recent project involving full interstitial space added $25.70/gsf to the cost of the building.

2. *Zoning and Code Implications*

Interstitial space impacts on zoning and code issues, as it necessitates greater building height for minimal additional net space. However, a certain amount of net space can be realized on a laboratory floor if electrical closets, air handlers, large shafts, etc., are located on unoccupied floors. Interstitial space also adds mass, resulting in architectural and structural considerations, influences floor area ratio, and affects the ratio of occupied to unoccupied space.

IV. ALTERNATIVE SERVICE METHODS

There are two other methods of incorporating a flexible service zone outside the laboratory proper but on the same level, thus adding square footage without additional floor-to-floor height.

The first is the traditional *service corridor*. In this concept, two laboratory or animal zones flank a service corridor measuring 6–12 feet wide. Rather than entering through the laboratories, the corridor is entered from either end, although there are usually entrances from the lab modules to allow researchers to travel through it as well. The service corridor is purely a building service space, and cannot be claimed as net square footage. All boxes, valves, electrical panels and services are accessed within this service corridor, and piping runs from the laboratories horizontally into this area.

A variation on this theme is the introduction of the *linear equipment room* (LER), a concept first employed at many US universities (Figure 13-6). In the LER, the building service space of a service corridor is designed for double duty. Serviceable components are located in the room so that service personnel do not have to enter the laboratory proper. In addition, it is designed to accommodate laboratory equipment that produces heat and noise, such as refrigerators and freezers, getting them outside the lab but immediately accessible. The LER is located between the laboratory and laboratory support zone, typically 11 feet wide, with designated 3-foot equipment zones on both sides and a 5-foot aisle. Offices are clustered and located across a corridor from the laboratory support zone. Laboratories are accessed through the laboratory support zone or through a contiguous office cluster. This is considered usable laboratory support space, and can be counted as net space or, in some instances, discounted. Advantages include high floor-plate efficiencies (75 percent); that laboratories adjacent to the LER can be opened or closed; that most serviceable components are located within the LER, minimizing disruption to laboratories or support rooms; and

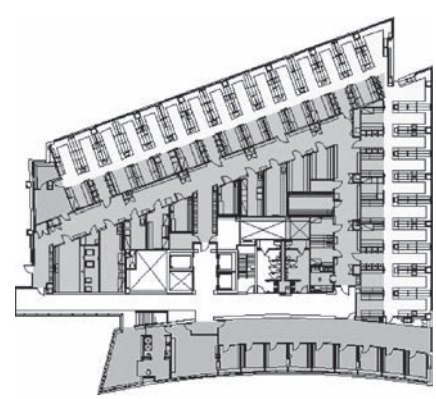

Fig. 13-6 Example of a linear equipment room (LER). Offices are in blue, LER in pink, laboratories in yellow (McDonnell Pediatric Research Building, Washington University, St Louis, Missouri).

that materials flow through a restricted, non-public space. Drawbacks include the distance between some offices and laboratories (up to 100 feet), and a high percentage of laboratory support space allocated to equipment rooms.

These alternatives to interstitial space also provide a level of flexibility beyond traditional construction, and can be weighed into any design process.

V. DESIGN REQUIREMENTS

To realize the true value and potential of interstitial space, planning must be meticulous. Utility and service patterns must be scrutinized not only for current requirements, but also for future changes. A well-organized design ensures that any reconfiguration will result in minimal downtime for scientists.

In the case of partial interstitial space, planning and design are crucial. Where the full-height space does not extend over the entire laboratory, services must evaluated and divided into those that can be reached from the interstitial space or catwalk and those requiring ceiling access, as the latter might cause an interruption of laboratory processes.

VI. CONCLUSION

Interstitial space in research buildings has advantages and drawbacks, and many owners and designers have strong opinions regarding its use. The best way to conclude whether or not interstitial space is the best solution is to answer some basic questions:

- Is the institution likely to take advantage of the flexibility that interstitial space allows by future reconfiguration or renovation of laboratory space?
- To what degree is “downtime” for routine maintenance detrimental to laboratories or animal housing areas?
- Is hazardous or sensitive research performed that will require maintenance and service personnel to take special precautions?
- Will another design or service method meet the need with less initial investment?

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Chapter 14

Hazard-resistant Building Construction

Catherine M. Vogelweid, James B. Hill and Robert A. Shea

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I. INTRODUCTION

Disasters occur everywhere, and they are natural phenomena that humans must accept and learn to deal with. Disasters have existed over time, and they will continue to cause significant disruption in human lives and activities unless we become better prepared to deal with their effects. Universities are vulnerable to the effects of natural disasters. In 2001, flooding from Tropical Storm Allison impacted vivaria at Baylor University and the University of Texas Medical School. The Texas Medical School vivarium was destroyed, and approximately 4,000 animals perished; their value was estimated at $7.4 million dollars. The damage to the vivarium

and its equipment totaled $105 million dollars. Remediation costs were $68 million dollars, and the cost of re-establishing the animal models is estimated at $7 million dollars. The cost to replace the building containing the research laboratories and vivaria is estimated at $80 million dollars (Schub, 2002; B. S. Goodwin, personal communication, November 2007). In 1997, many research animals drowned during floods at the University of North Dakota, which sustained damages totaling $46 million dollars. The 1995 earthquake in Kobe, Japan, destroyed the medical school's vivarium, culminating in the deaths of 4,000 research rodents (Normile, 1995; Witt, 2004). These examples point out that many different types of hazard events can occur, and that their impact on vivaria can be devastating.

Because humans tend to think of disasters as low-probability, high-consequence events, it seems easier to forget about them than to plan to deal with them (FEMA, 2003a). Unfortunately, the current emphasis on disaster preparedness in the laboratory animal profession has been focused almost exclusively on the implementation of response plans, which are activated after a disaster occurs. The examples cited in the preceding paragraph show that post-disaster rescue attempts have been unsuccessful in saving animals' lives. Disasters can happen so fast that evacuation cannot be accomplished, or the building may sustain so much damage that re-entry of rescue personnel is deemed unsafe and will not be permitted. Disaster-response plans are needed for emergency response during a disaster, but they should not be relied upon as the sole means of protection for research animals in a vivarium.

Local or national building code standards are centered on the provision of life safety for humans occupying the structure, and they do not address either life safety or essential support activities for the other living and essentially permanent residents of research buildings – the animals. In addition, the Federal Emergency Management Agency (FEMA) cites the presence of large numbers of buildings in floodplains and the lack of attention to earthquake risk in the Midwestern United States as specific examples where communities have largely chosen to ignore the risks posed by natural hazards (FEMA, 2004a). Because building codes do not protect animals and many communities allow construction of new buildings in hazardous areas, the laboratory-animal professionals must be knowledgeable about local hazards and diligent in their efforts to address the concept of providing additional protection for the animals.

Disaster-mitigation professionals recognize that the most effective strategy for reducing potential losses during a disaster is to minimize or prevent damage to buildings. Since 1997, FEMA has been advancing the idea that catastrophic losses do not have to occur along with disasters. FEMA has developed pre-disaster initiatives, *Project Impact: Building a Disaster Resistant Community* and *Disaster-Resistant Universities*, to identify and correct vulnerable areas in communities before a disaster strikes. FEMA recognizes that any actions that a business or institution can take beforehand to minimize the structural damage to its buildings and increase the safety of its occupants will reap huge dividends when the business needs to resume operations following a disaster. Instead of relying only on disaster-response plans, we should also be protecting research animals by housing them inside safer vivaria.

II. BEGIN PLANNING DURING THE PROGRAMMING PHASE: ESTABLISH HAZARD/ DISASTER PLANNING AS A MINDSET

Disaster planning should begin during the programming phase of the architectural design process. The first step is to disregard the all-too-familiar attitude to disasters: "That could never happen to us."

There are some important misconceptions about building codes and building safety that are common among design professionals (architects and engineers) and laboratory-animal professionals that require clarification at the outset of the design process. Laboratory-animal professionals and design professionals usually do not interpret building evacuation procedures and compliance with life safety codes similarly. For example, architects and engineers usually design a research building under the assumption that either all occupants are independent and can evacuate promptly during an emergency, or that occupants that cannot evacuate on their own can rapidly retreat to an area of rescue until they can be assisted. When a vivarium houses thousands of animals, timely movement of them will not be possible; humans will have to leave first, and then come back later for the animals. Therefore, it is essential that the building's structural system remains intact and that the vivarium remains safe for humans to re-enter in the immediate post-disaster period. This is not possible if the building sustains significant structural damage. Laboratory-animal professionals generally assume that buildings that are compliant with life safety codes are safe, and they will be able to achieve some minimum level of function in the post-disaster period. In contrast, design professionals know that life-safety codes provide for structural integrity of the building only for the duration of the anticipated evacuation period during the design disaster event. It is possible for a code-compliant building to be severely damaged and uninhabitable following a disaster.

Everyone on the design team needs to understand that the inclusion of a vivarium in a research building will place unique demands on the design of the building. The intended level of performance of the building in terms of life safety for both humans and animals, the levels of damage that would be acceptable, and the expected amount of post-disaster functionality of the building should be discussed for each relevant hazard, and a set of performance objectives for the building should be developed by the building owner's team in consultation with the design professionals and the authority having jurisdiction (if any). Performance-based engineering has been most commonly applied in seismic design, where two performance levels for both structural and

non-structural components of the building are defined: Life Safety, and Immediate Occupancy. The Life Safety performance level contains two performance criteria in the design evaluation: (1) there is some margin against either partial or total structural collapse; and (2) human injuries may occur as a result of failures in building system components (structural and non-structural), but the overall risk of life-threatening or fatal injuries as a result of structural collapse is expected to be low. The Immediate Occupancy performance level also contains two performance criteria in the design evaluation: (1) the basic vertical and lateral force-resisting systems retain nearly all of their pre-earthquake strength; and (2) there is only minor damage to both structural and non-structural components and critical parts of the building are habitable. These calculations are derived after specifying the design earthquake event, which is the magnitude or size of the earthquake that the building owner's team wishes to protect the building from. Essential facilities in a community, such as a hospital, are usually designed to the Immediate Occupancy performance level; research buildings are typically designed to the Life Safety performance level.

III. CONDUCT A RISK ASSESSMENT OF THE EXISTING PROGRAM AND FACILITIES

It is essential to determine what risks exist in the current program and facilities before proceeding with the design of the new vivarium. It is necessary to discuss the economic value of the research and the animals, the asset value of existing buildings and their contents, and the consequences anticipated if these components are lost. The risk assessment for the program is not done solely by the planning team. It should be conducted by a group of individuals selected for their broad base of knowledge about institutional or corporate policies and risk management, and those with knowledge of the physical infrastructure of the buildings and the operational procedures that impact each existing vivarium, both on a day-to-day basis and during an emergency. Some institutions have planning organizations already in place at the university, college, school or division level that could provide information and receive input about hazards. At other institutions, the appropriate contact person might be a chancellor or dean. Representatives from the laboratory-animal staff may include the animal program or facilities director, IACUC chair, veterinarians and facility managers. Public safety representatives (fire and police), environmental health and safety personnel and facilities maintenance staff can address the adequacy of existing emergency-response capabilities and building function, and they can often identify existing hazards near the animal facilities that animal facility staff might be unaware of. Risk-management staff can provide information about insurance coverage. FEMA has published several useful "how-to" guides to assist businesses and institutions in estimating the value of their assets and estimating their loss potential (FEMA, 2001a, 2003b, 2004b).

Steps to conduct a risk assessment include:

1. Identify hazards
2. Determine their likelihood of occurrence
3. Assess the vulnerability to hazards
4. Risk-management strategies
5. Asset recovery.

A. Identify Hazards

In its simplest form, risk is estimated by the following formula (FEMA, 2003a):

$$\text{Risk} = \text{hazard} \times \text{vulnerability}$$

The first step is to identify the types and frequencies of occurrence of both natural and manmade hazards that are operable on the existing research program.

1. *Natural Hazards*

Information about susceptibility to natural hazards should be obtained from multiple sources. The planning team can acquire reliable information about natural hazards risks from their local county and state emergency planning offices. Ideally, the county and state emergency planning offices have already identified and ranked the relevant natural hazards at the locations of existing buildings and the proposed construction site as part of their local governments' emergency plans. These professional planners may also have experience with FEMA's HAZUS software, which allows individual institutions or businesses to prepare detailed, specific risk assessments for their organizations. Newspapers, historical records and hazard websites are also valuable sources of information. Table 14-1 lists reference sources that the authors have found particularly valuable.

2. *Manmade (Technological) Hazards*

Technological hazards include flammable chemicals, explosive materials, biologicals, chemicals and radiological agents. The locations and types of technological hazards that are present within a community are often not widely known by the general public. Without further investigation and inquiry, a new research building could be constructed in close proximity to existing buildings where large quantities of hazardous materials are kept, or along their transportation routes. It is quite common for biomedical research laboratories and animal facilities to use and store hazardous chemicals – examples include concentrated disinfectants, chemicals used in cage-washing machines, cylinders containing compressed gasses, and tissue fixatives. Many research laboratories also use radio-isotopes and infectious agents in animals for diagnostic or therapeutic research studies. Additionally, radio-isotopes are sometimes generated on-site using a cyclotron.

TABLE 14-1

REFERENCE SOURCES FOR INFORMATION ON NATURAL AND TECHNOLOGICAL HAZARD RISKS

Natural hazard type	Reference publications
General–describes all hazards	*Multihazard Identification and Risk Assessment: A Cornerstone of the National Mitigation Strategy*, FEMA, Washington, D.C., 1997. *State and Local Mitigation Planning How-To Guide: Understanding Your Risks, Identifying Hazards and Estimating Losses*. FEMA 386-2, Version 1.0, August 2001. Available at www.fema.gov. *State and Local Mitigation Planning How-To Guide: Integrating Human-Caused Hazards into Mitigation Planning*. FEMA 386-7, Version 2.0, September 2003. Available at www.fema.gov. *Animal Management In Disasters* by Sebastian E. Heath, Mosby, Inc., 1999. The FEMA website for hazard maps is www.hazardmaps.gov.
General building information & fire	2006 International Building Code (IBC). *American Society of Civil Engineers Minimum Design Loads for Buildings and Other Structures* ASCE/SEI 7-05. *NFPA 150 Standard on Fire and Life Safety in Animal Housing Facilities*, 2007 edn, available from the National Fire Protection Association.
Flood	Flood Insurance Rate Maps (FIRMs) are available from FEMA at www.fema.gov/fhm. The FEMA website for flood mitigation is www.Floodsmart.gov. *Protecting Building Utilities from Flood Damage: Principles and Practices for the Design and Construction of Flood Resistant Building Utility Systems*. FEMA 348, 1st edn, November 1999. Available at www.fema.gov.
Earthquake	*Seismic Considerations—Health Care Facilities. Earthquake Hazards Reduction Series 35*. FEMA 150 / Revised May 1990. *National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, 2000 edn. FEMA 369. Available at http://www.bssconline.org/NEHRP2000/comments/. Shaking Hazard Maps are available from the United States Geological Services Website at http://quake.wr.usgs.gov/prepare/factsheets/RiskMaps/. *Design Guide for Improving School Safety in Earthquake, Floods and High Winds*. FEMA 424, January 2004. Available at www.fema.gov. *Primer for Design Professionals: Communicating with Owners and Managers of New Buildings on Earthquake Risk*, FEMA 389, January 2004. Available at www.fema.gov. *Typical Costs for Seismic Rehabilitation of Existing Structures*, Vol. 1, *Summary*, 2nd edn, December 1994. FEMA 156. Available at www.fema.gov. *Typical Costs for Seismic Rehabilitation of Existing Buildings*, Vol. 2, *Supporting Documentation*, 2nd edn. FEMA 157, September 1995. *Pre-standard and Commentary for the Seismic Rehabilitation of Buildings*, 2000, FEMA 356, November 2000.
Tornado/high winds	*Design and Construction Guidance for Community Shelters*. FEMA 361, July 2000. Available at www.fema.gov. *Design Guide for Improving School Safety in Earthquake, Floods and High Winds*. FEMA 424, January 2004. Available at www.fema.gov.
Hurricane	*Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing and Maintaining Residential Buildings in Coastal Areas*. FEMA 55, June 2000. Available from the FEMA Mitigation Directorate at www.fema.gov.

B. Determine Likelihood of Occurrence

Once the types of relevant hazards are listed, their likelihood of occurrence should be determined. The probability of the occurrence of the common natural hazards is often expressed as the "mean recurrence interval – the average time in years between the expected occurrence of an event of a specified intensity" (FEMA, 2004a). One example is the level of the 100-year flood. This level is often used as a reference point to define minimum flood elevations for construction within a community. While most persons might think that it is safe to build at the elevation of the 100-year flood, professional disaster planners understand that a recurrence interval is only an estimate of probability that is averaged over a very long period of time. Recurrence intervals do not imply that a flood will occur only once every hundred years – this is a very common public misconception. In reality, natural events equaling or exceeding those specified in the recurrence intervals can occur at any time.

The approximate quantities and locations of technological hazardous agents may be known by environmental health and safety staff, emergency first-responders (fire and police) or local government emergency planners. When evaluating the risks posed by technological hazards, it should be determined how the presence of these materials might impact the building or the surrounding environment during a disaster. For example, seepage of radio-isotopes and chemicals from a research building into floodwaters will contaminate the surrounding

environment, creating a large hazmat incident that impedes additional emergency response efforts in the building. Such contamination could delay or prevent the evacuation of animals from the vivarium.

C. Assess Vulnerability to Hazards

1. *Determine the Economic Value and the Vulnerability of the Existing Research Program*

The economic value of the assets of the research program should be estimated. Once the hazards have been identified and the probability of occurrence established, research buildings located in susceptible areas should be considered as being at risk. The costs (in today's dollars) to replace at-risk buildings and their contents, the costs associated with displacement if occupants have to be moved to a different building while the damaged building is undergoing repairs, the estimated lost income from inability to conduct normal business operations, plus the potential loss of income received from biomedical research grants and contracts/services provided, should be summed in an effort to quantify the value of the program assets that are currently at risk. FEMA provides charts and guidelines for reference (FEMA, 2001a, 2003b).

2. *Identify and Review Any Problems With Existing Facilities*

The risk assessment should also identify any problems with the operations or physical infrastructure of the existing research buildings and vivaria. This information will be used by the planning team to avoid repeating past mistakes as the new building is designed.

D. Risk Management Strategies

Any existing risk-management strategies that are already in place at the institution or business should be evaluated for their ability to cover the value of the assets identified as being at risk. In general, risk-management strategies are geared towards reducing losses in three general categories: (1) loss of life (humans or animals); (2) loss of assets (buildings and their contents); and (3) loss of business functions (services provided and generation of revenue) (FEMA, 2001a). An institution or business may choose to reduce its risks of losses to an acceptable level by developing plans that decrease losses in one, or in combinations, of these three categories. For example, risk of loss of life can be reduced by having an institution or company safety plan in place, and by developing and practicing good evacuation plans. Disruptions in business functions can be managed by diversifying operations and by developing recovery programs that speed up resumption of normal business activities. A business or university can achieve diversification by maintaining its essential service units at geographically separate locations. Critical electronic records and operational data from the vivarium, including sources of animals, census data, numbers of animals purchased and pertinent medical records should be backed up frequently and maintained at a geographically separate site. The reliability and integrity of the back-up system should be periodically verified. Diversification can also be adopted as a strategy to protect against the total loss of valuable animal models – small breeding colonies can be maintained at multiple geographic locations, or genetic material or embryos cryopreserved and stored off-site. At academic sites, the procedures for backing up and retrieving research data warrant special consideration, because FEMA reports that this is an especially vulnerable area of loss at universities (Witt, 2004).

E. Asset Recovery

Asset recovery through insurance is another method of protection against economic catastrophe following a disaster. When the total value of the assets of the institution exceed $50 million dollars, it becomes increasingly difficult to obtain independent insurance coverage (FEMA, 2004b). As the costs of incorporating new technology into buildings and construction costs escalate, it is unlikely that the insurance coverage at most institutions will be able to keep pace, and many may wind up under-insured and unable to replace their assets.

At the conclusion of the risk assessment, the planning team for the new vivarium can focus its design efforts on reducing the impact of common, significant hazards, because they will have in-hand information that is both relevant and realistic. Problems inherent in previous designs are identified. If an institution or business does not have an adequate risk-management plan in place or enough insurance coverage to replace its assets, there is better justification for incorporating additional protection into the design of the new vivarium.

1. *Example*

As an example, we include a vulnerability analysis for a university campus in the Midwestern United States, having modified a chart used by FEMA to fit the animal facilities and operations (American Red Cross, 1993). Every hazard that might occur at each animal facility was listed and assigned a frequency of low, moderate or high. High-frequency events had occurred or were deemed very likely to happen. Medium-frequency events were likely to occur in the future. Low-frequency events were expected to occur rarely, or there were already protective measures or systems in place to prevent the event from causing any impact on the program or research animals. Each event was then scored for its impact in six categories: impact on humans, impact on animals, impact on overall operations, facility construction vulnerability, strength of local emergency response, and strength of city/county emergency response. The maximum possible score, an "End of the World"

type of event, was 30 (six categories times an impact score of 5 for each category).

Criteria used to assess the facility construction vulnerability included the following:

1. An evaluation of each existing building containing an animal facility for risk relative to FEMA hazard maps for flood, earthquake, high winds, snow and ice storms, and tornado (Midwestern natural hazards)
2. A listing of the level of existing animal facilities within the buildings (basement/grade/above grade) and the percentage of the total animal population that was residing at each level
3. The mechanical and electrical systems in each building (type, redundancy of lifeline systems, location within the building)
4. The age of the building and compliance with life safety, fire and seismic codes.

The impact scoring system is summarized in Table 14-2. Summary information about existing animal facilities and an example of the vulnerability analysis for Facility A are described in Tables 14-3 and 14-4, respectively. The results of the vulnerability analysis for all facilities are summarized in Table 14-5. Reference sources for obtaining information on

TABLE 14-2

IMPACT SCORING SYSTEM

Impact category	Impact score	Description
Impact on humans	0	The event would have no impact.
	1	The event would produce a few minor injuries and have limited psychological impact.
	2	The event would produce minor injuries and have moderate psychological impact on several persons.
	3	The event would produce many injuries, some of them serious.
	4	The event would produce many serious injuries, a few deaths are possible.
	5	The event would produce many serious injuries & many deaths.
Impact on animals	0	The event would have no impact.
	1	The event would produce a few minor physical injuries.
	2	The event would produce minor injuries in many animals.
	3	The event would produce many injuries, some of them serious. Animals remain contained within the vivarium.
	4	The event would produce many serious injuries and some deaths. Some animals escape.
	5	The event would produce many serious injuries and many deaths. Many animals escape. The vivarium could be destroyed.
Impact on overall operations	0	All facilities are operating normally after the event occurs.
	1	The event has minimal impact on operations. All facilities except where the event occurs are operationally normal and the impacted facility is functional.
	2	The event has minimal impact on operations. All facilities except where the event occurs are operationally normal. The impacted facility is not functional.
	3	The event causes some disruption of normal operations. Several facilities are affected.
	4	The event causes moderate disruption of operations. Several facilities cannot achieve normal operations. Some facilities are severely damaged.
	5	The event disrupts normal operations at all facilities. Some facilities are severely damaged or destroyed.
Facility construction vulnerability	0	Existing construction features of the building lessen or prevent the effects of the event.
	1	The building construction and vivarium are neutral if the event occurs.
	2	The building construction and vivarium are neutral if the event occurs.
	3	If the event occurs, the location of the vivarium in the building places it at a distinct disadvantage. No other features of the building increase the hazard posed by the event.
	4	The vivarium is at a disadvantaged location and the building's construction possesses inherent weaknesses that could impair response capability during the event; *or* the building is too old to meet current life safety, fire and earthquake code standards but there is no evidence of deterioration.
	5	The vivarium is at a disadvantaged location within the building and there are nearby hazardous materials that could escalate the severity of the event; *or* the building is too old to meet current life safety, fire and earthquake code standards and there is evidence of deterioration; *or* a large event would be expected to destroy the building.
Strength of local emergency response	0	No emergency response is needed to handle the event.
	1	Local units can quickly and effectively handle the event.

(Contd.)

TABLE 14-2
CONTINUED

Impact category	Impact score	Description
	2	Local units can effectively handle the event in a reasonable length of time.
	3	Local units can handle the event, but more time and multiple units are needed.
	4	Local units encounter difficulties managing the event and they are working beyond their capacity; city and/or state units are called to assist.
	5	The event is expected to overwhelm local response capability.
Strength of city/ county response	0	No emergency response is needed to handle the event.
	1	Local units are able to manage the event, no county response units are not activated.
	2	Local units can manage the event, city and county response units are not activated.
	3	City and county response units are activated and able to contain the event.
	4	City and county response units are activated, multiple units respond to the event; assistance is requested from neighboring jurisdictions and the state.
	5	City, county & state response units are overwhelmed, federal disaster declaration occurs.

TABLE 14-3
SUMMARY INFORMATION FOR EXISTING ANIMAL FACILITIES

Facility and year constructed	Percentage of total animal population	Floor level of animal facility	Elevators with emergency power	Cooling source	Heating source	Floor level of emergency generator	Floor level of main electrical equipment
A 1986	60%	Basement	Yes–freight & passenger	Campus	Campus	Basement	Basement
B 1996	10%	Basement	Yes–passenger	Campus	Campus	Basement	Basement
C 1998	20%	Sub-basement	Yes–passenger	Campus	Campus	Basement	Basement
D 1958	5%	Fourth	Yes–passenger	Campus	Campus	Campus power plant	Basement
E 1989	5%	Third	Yes–passenger	Campus	Campus	Unknown	Basement

TABLE 14-4
VULNERABILITY ANALYSIS: EXAMPLE FOR INDIVIDUAL FACILITY A

Event	Frequency	Human impact	Animal impact	Operations impact	Facility construction vulnerability	Strength of local response	Strength of city/ county response	Total score
Internal flood	High	2	3	3	4	1	1	14
Winter storm	High	2	1	3	2	1	1	10
Emergency medical event (fall, heart attack)	High	2	0	1	0	0	0	3
Explosion	Medium	4	4	4	3	3	3	21
HAZMAT incident	Medium	2	2	3	3	2	1	14
Animal Rights protest / vandalism	Medium	2	0	3	2	1	1	9
Elevator outage	Medium	1	0	1	2	0	0	4
Workplace violence	Medium	2	0	2	0	0	0	4
Earthquake	Low	5	5	5	2	5	4	26
Fire	Low	4	4	4	3	2	2	19
Tornado	Low	4	4	4	1	3	3	19
72-hour power loss	Low	2	5	4	4	2	1	18
External flood	Low	3	5	5	4	4	3	24

TABLE 14-5
RESULTS OF VULNERABILITY ANALYSIS FOR ALL EXISTING ANIMAL FACILITIES

Event type	Estimated frequency	Facility A (basement)	Facility B (basement)	Facility C (sub-basement)	Facility D (4th floor)	Facility E (3rd floor)	Average event score
Internal flood	High	14	13	14	10	8	12
Winter storm	High	10	9	9	10	10	10
Elevator out 72 h	High	4	9	6	12	11	9
EMT event	High	3	7	5	3	3	4
Explosion	Medium	21	18	21	20	19	20
Fire	Medium	19	17	19	19	19	19
HAZMAT spill	Medium	13	13	13	12	12	13
Animal rights/vandals	Medium	9	7	8	9	10	9
Workplace violence	Medium	4	4	4	4	4	6
Earthquake	Low	26	25	25	26	26	26
Tornado	Low	19	18	19	21	20	20
External flood	Low	24	20	25	12	12	19
72-h power/HVAC out	Low	18	15	16	16	13	16

the risks of natural hazards in various regions of the United States are provided in Table 14-1.

The example reveals areas of weakness in the existing facilities, and ranks each type of disaster by its anticipated impact on the program. Earthquake, tornado, explosion, fire and external flood are expected to have the largest negative impacts on the program (refer to Table 14-5). Fortunately, the frequency of all of these hazards is low, with the exception of explosion, which evaluators scored at medium frequency. The analysis reveals a substantial weakness in the existing program – 90 percent of the current animal population resides below grade in buildings in which the emergency generator and main electrical equipment are also located below grade (Facilities A–C, Tables 14-3 and 14-4). It is highly likely that the animal facilities, emergency generators and electrical service to the buildings would all be incapacitated in a flood. Although the anticipated frequency of external flooding is low, the occurrence of internal flooding in these buildings and flooding from storm run-off are possible. Thus, these animals remain at risk. The team concludes that the pre-existing construction features that were responsible for the risks of explosion and flood hazards should not be repeated in the design of the new vivarium.

IV. CREATE A CONCEPTUAL RISK ASSESSMENT FOR THE PROPOSED ANIMAL FACILITY

A conceptual risk assessment is created by listing the relevant hazards that are possible on the proposed building site (refer to Table 14-1 for reference sources for assessment of natural hazards and their mitigation). Next, the important operational and program elements for the vivarium are listed. The hazards and program elements are then subjectively scored relative to one of three theoretical locations for the animal facility within the building: basement, grade or upper level. If a location is a preferred site for a program functional element or if it would be safer than other levels if a specific disaster occurred, a score of +1 is assigned; if the location is neutral, a score of 0 is assigned; if the animal facility or function is at a disadvantaged location, it is scored as −1. Finally, the results at each theoretical location within the building are summed to generate a numerical score.

Examples of the conceptual risk scoring for natural disasters, manmade hazards and program elements for our new animal facility constructed in the Midwestern United States are summarized in Tables 14-6–14-8, respectively. In this example,

TABLE 14-6
CONCEPTUAL RISK ASSESSMENT FOR NATURAL DISASTERS FOR AN ANIMAL FACILITY LOCATED IN THE MIDWESTERN US

Disaster type	Basement	Grade	Upper level
Winter storm	0	0	0
Tornado	+1	−1	−1
Flood	−1	0	+1
Earthquake	+1	0	−1
Total score	+1	0	−1

TABLE 14-7
CONCEPTUAL RISK ASSESSMENT FOR MANMADE HAZARDS FOR AN ANIMAL FACILITY LOCATED IN THE MIDWESTERN US

Hazard type	Basement	Grade	Upper level
Elevator failure	−1	+1	−1
Internal flood	−1	0	+1
Fire/smoke	0	+1	0
Total score	−2	+2	0

TABLE 14-8

CONCEPTUAL RISK ASSESSMENT FOR PROGRAM FUNCTIONS FOR A NEW ANIMAL FACILITY LOCATED IN THE MIDWESTERN US

Program element	Basement	Grade	Upper level
Security/access control	+1	−1	+1
No dependency on elevators	−1	+1	−1
Animals adjacent to labs	−1	0	+1
Ease of materials access	−1	+1	−1
No exterior windows wanted	+1	−1	−1
Noise/odor control	+1	0	0
Ease of emergency egress of animals	−1	+1	−1
Total score	−1	+1	−2

the basement is the preferred location to mitigate against the natural disasters expected to occur in the geographic region, while the grade level is both the preferred location to mitigate against manmade hazards and the level that best meets the important program elements as defined by the users. Our conceptual risk assessment concludes that the grade level is the optimum site for the new animal facility.

A. Decide What Level of Function Would Be Desirable in the Vivarium After a Disaster

After reviewing the information generated during the risk assessments, the owner and design team gain an impression of the current scope and value of the research program and the likelihood that the current assets are adequately protected from loss. The level of acceptable risk for the planned facility can then be decided by the building's owners. The critical question to be answered when determining the acceptable level of risk is the following: if the new building and vivarium are designed strictly to minimum code requirements, are the damages and losses that might occur following a disaster acceptable? The answer to this question sets the stage for meaningful discussions about whether the incorporation of additional safety features into the design of the new vivarium and research building is warranted.

The design for the new research building and the vivarium will be a compromise between maintaining the functions required of the research program, providing disaster-resistance, and the amount of money available to invest in improving the design above minimum standards. In most cases, it will not be possible to construct a vivarium that will not be damaged when the magnitude of the disaster is large. However, it is possible to incorporate additional design features that will either reduce physical damage to the building, allowing the vivarium to resume its critical functions more quickly following a disaster, or to enable the evacuation of animals in a reasonable amount of time. The costs associated with incorporating additional safety features are variable, depending upon the level of protection desired and the risk of exposure of the building to a specific hazard. Examples of items that can be incorporated at essentially no increased cost include locating the vivarium in a safe area of the building, installing doors and doorframes along evacuation routes that can accommodate the passage of animal racks and cages, and programming reheat coils to fail "off" so that animal rooms do not overheat when power is restored to the HVAC system. Adding redundancy to mechanical and electrical equipment systems, increasing the availability of emergency power in the vivarium, and structural reinforcements will be associated with increased construction costs. As a general reference, the increases in costs are best known from earthquake mitigation projects. FEMA reports that including seismic structural reinforcement at the beginning of the design phase of the building only increases the cost of construction by approximately 1.5 percent (FEMA, 1990).

While no specific guidelines have been developed for reinforcement of the vivarium, the *International Code Council Performance Code for Buildings and Facilities* (ICC, 2003), the 2000 *National Earthquake Hazards Reduction Program Provisions* (*NEHRP Provisions*) (FEMA, 2001b) and the 2007 edition of the *NFPA 150 Standard on Fire and Life Safety in Animal Housing Facilities* (NFPA, 2007) can be referenced as a starting point for deciding what level of protection might be appropriate for research animals. The *ICC Performance Code for Buildings and Facilities* and the *NEHRP Provisions* establish the minimum requirements for construction of an individual building by considering the total number and types of occupants in the building, as well as its intended use. Some buildings in the community are designated as "essential facilities" – they must remain functional after a disaster. The design and construction requirements cited in building codes for essential facilities are more stringent than for most other types of buildings. Examples of essential facilities include hospitals and emergency shelters. In addition to essential facilities, most building codes require reinforced construction when a building will contain a large number of occupants who cannot evacuate independently – a school containing children is an example. A building may also require reinforced construction methods if it will contain quantities of hazardous materials that are large enough to cause environmental contamination if these materials are released from the building during a disaster. Similar logic can be extrapolated and applied to research programs. If a planned vivarium will house a significant component of the total research animals in the program, if the experimental models are unique and irreplaceable or if the vivarium will contain significant quantities of hazardous materials, the design team should consider the incorporation of additional safety features. For example, the inclusion of a cyclotron or planning to conduct research studies with infectious agents at Animal Biosafety Levels (ABL) 3 and 4 would warrant the incorporation of additional protective features to safeguard against the release of radio-isotopes and hazardous infectious agents into the environment. Institutions may also

decide that additional protection is warranted for humane considerations, as well as to avoid the potential negative publicity associated with mass casualties of research animals.

The *NFPA 150 Standard on Fire and Life Safety in Animal Housing Facilities* provides the minimum requirements for the design, construction, fire protection and classification of animal housing facilities. The Standard subdivides animals into categories based upon their potential to pose significant risks to rescuers (or to the general public) and whether it would be feasible to move the animals efficiently during a disaster or an emergency. The Standard provides recommendations to design and construct animal facilities so that animal occupants and their human caretakers are protected from the spread of fire, and to enable the timely evacuation of animals should that become necessary. This document applies to all structures that house animals, including zoos, veterinary clinics, pet stores and horse stables at racetracks. The standard is based on the assumption that many species of animals would not be expected to cooperate during an evacuation; thus, the standard proposes that additional safety measures be incorporated into egress pathways so that animals can be evacuated without causing injuries to humans. Some of the general problems that are identified and addressed in this document can be extrapolated directly to the research animals in the vivarium (NFPA, 2007).

The ICC Code standards and the 2000 *NEHRP Provisions* describe, in general terms, the expected impact on the building's structure, internal components and occupants if a large hazard event were to occur (Table 14-9). It is critical that the vivarium's planners understand that compliance with standard minimum construction code, i.e., the Life Safety Code, means that the vivarium will most likely sustain damage at a high impact level. Significant disruption of the building's structural support system and internal components are expected. The building may not be able to provide the life-sustaining support services that research animals will require in order to survive (electricity, ventilation, potable water, and limited temperature and humidity control). In contrast, designing the vivarium to a more stringent code, such as hospital code, or including additional reinforcement of some of the building's components, could limit damage to a moderate amount. Such a building should be able to provide life-sustaining services for animals in the immediate post-disaster recovery period. In seismic design terminology, such a building would be able to achieve Immediate Occupancy functions.

V. CORE CONCEPTS FOR DESIGN OF THE NEW VIVARIUM

With the results of the vulnerability assessment and the conceptual risk assessment in hand, the owners, architects and engineers can approach the design of the new building and vivarium with an educated disaster mindset. The vulnerabilities in the existing program are recognized. The risks inherent in the existing facilities are identified and understood. A scorecard of risk issues and program elements versus stacking location within the building is in hand to challenge or validate design phase decisions.

A. Methods That Can Be Used to Achieve Hazard-resistant Design in the Vivarium

The design team and building owner should by now understand that designing a building for damage-free performance

TABLE 14-9

EXPECTED LEVEL OF DAMAGE TO A BUILDING DURING A DISASTER: FROM MILD LEVEL OF DAMAGE TO SEVERE IMPACT

	Mild impact	Moderate impact	High impact	Severe impact
Effect on structural system of the building	No damage, safe to occupy	Moderate, repairable damage	Significant damage, but no falling debris	Significant damage, debris, danger of building collapse
Effect on non-structural components (HVAC, utilities), equipment and contents	Minimal damage	Moderate damage, but repairable	Significantly damaged and inoperable; emergency systems are damaged, but operational	Destroyed or significantly damaged, emergency systems are substantially damaged and non-functional
Effect on building's occupants	A few minor injuries occur	A moderate number of moderate injuries occur; few or no deaths	A moderate number of life-threatening injuries occur; moderate risk of some deaths occurring	Many life-threatening injuries and many deaths
Effect on environment	Hazardous materials not released	Hazardous materials released in building, but no risk posed to community	Hazardous materials released into environment, but local containment is adequate & community is not affected	Hazardous materials released, contamination spreads beyond immediate vicinity of spill; community affected
Building code design standard		Hospital Code	Life Safety Code	
Seismic design performance level	Operational Level function	Immediate Occupancy function	Life Safety Level function	Near collapse level

during a large disaster event is not possible, but it *is* possible to limit the amount of damage that occurs and to enhance the restoration of life-sustaining services for animals in the vivarium. The incorporation of disaster-resistant design into the vivarium can be accomplished in three general ways: by adopting design standards similar to hospital code in the vivarium, by using performance-based design to achieve specific building-performance objectives, or by incorporating areas of shelter and refuge into the vivarium. The method or methods selected by the design team will likely depend on their familiarity with a method, the amount of financial resources available for hazard mitigation, and the specific types of hazards.

Design standards for hospitals are more stringent than general code requirements for research buildings. In the vivarium, designers may wish to incorporate the requirements in hospital code for increased seismic protection, fire ratings, smoke zones and egress paths. Specific examples include upgrading engineering systems to enable more accurate and timely detection of fires, installing more smoke detectors, creating barriers to limit the flow of smoke, and placing visual indication devices in animal holding areas. The incorporation of structural elements to an Immediate Occupancy performance level will allow animal-care personnel to safely re-enter the vivarium after a disaster. Structural and non-structural components, such as drywall partitions and cladding, should be designed and attached to ensure that egress paths are not obstructed. Creating spaces for containment of smoke and better ability to detect the location of fires will provide more opportunities for timely interventions, through enhanced ability to evacuate animals or faster suppression of fires. These general principles are reiterated in the *NFPA 150 Standard for Fire and Life Safety in Animal Housing Facilities* (NFPA, 2007).

Performance-based design is a new idea that allows design professionals to use advanced analytical tools and computational methods to achieve a building design that will perform predictably during disasters. With performance-based design, the new building is designed to meet a consensus set of performance objectives. The objectives specify the performance of the building with regard to life safety, levels of tolerable damage, and level of function expected in the building after the disaster. The objectives are selected after close examination of the hazards and vulnerability. To date, performance-based design has been applied mainly in the field of earthquake engineering.

Selected areas within the vivarium or specific animal rooms could be constructed to serve as internal sheltering areas for animals. In cases where mitigation against high winds is desired, the walls can be designed to a performance standard that includes resistance to penetration by projectiles. In areas of low seismic risk, this can be accomplished by constructing reinforced concrete masonry walls, using 14-gauge metal for doors, and selecting solid doors with no window openings (FEMA, 2000).

B. Select an Appropriate Site for the Building

The planning team should strive to select a building site with the least risk for natural and technological disasters. It is important to consider all hazards that may occur at the site. Ideally, sites with one or more catastrophic weaknesses should be eliminated from further consideration. For example, a site in the Midwestern United States that is located within the 500-year floodplain on compacted fill or unstable soil is unsuitable for building a vivarium because it is vulnerable to flooding, and the type of soil also makes it inherently unstable during an earthquake. The future use of this site would be better served by assigning it to a less critical function. On a college campus, such uses might include a parking lot, or open recreational space.

In reality, building sites are usually pre-determined, with little or no consideration of disaster planning. Buildings are constructed in specific areas because of proximity to other existing buildings, or because the land was easily purchased or previously acquired for development. In these cases, any inherent weaknesses of the selected site will have to be reconciled by design or modification of the site, or in the design of the building. If another site is available, relocation of the proposed building is likely the least expensive solution.

C. Choose an Overall Design for the Building that Mitigates Against Multiple, Relevant Hazards

It is important to use an integrated, multi-hazard approach in the overall building design so that the best balance is achieved between the hazards and the methods chosen to protect the building. In some cases, the protection methods will be compatible across different types of hazards. Selecting a plan and elevation for the building that is symmetrical and regular in shape is recommended as a simple and cost-effective protection method, because this building form tends to evenly distribute the forces placed on the building during a disaster. Thus, careful selection of the configuration of the building is one way to reduce its vulnerability to structural damage in earthquake, flood, high wind and explosion. In other cases, the methods of protection may conflict between different types of hazards. For example, mounting large, heavy HVAC equipment on the roof will protect it from flood damage, but this practice increases the likelihood that it will be damaged during an earthquake, hurricane or wind storm. Oftentimes, a material can be altered or reinforced to make it perform acceptably during a disaster. For example, epoxy-painted unreinforced concrete block is commonly used to construct the walls of animal rooms, and disaster construction literature unanimously reports a high failure rate for this material during many types of disasters (earthquake, flood, high winds, explosion and fire). However, concrete masonry block walls with reinforcing steel in grouted cells perform much better. The reader is referred to Chapter 3 in the *Design Guide for Improving School Safety In Earthquakes, Floods and High*

Winds (FEMA, 2004a) for a comprehensive comparison of specific protection methods for building systems.

D. Select a Floor Level for the Vivarium that Minimizes Risk

The results of the conceptual risk assessment have to be evaluated in context with the total building program. The ultimate goal during the design phase is to achieve the best balance between the needs of the animal program, within the context of the total building program and budget. All components should be located so that day-to-day operational needs, important program elements and disaster planning needs achieve the best balance. The results of the conceptual risk assessment done during the planning phase can assist in evaluating how the new vivarium "stacks" within the facility.

The vivarium should not be located below grade in areas where flooding is recognized as a potential natural hazard. On the other hand, it *is* desirable to locate the vivarium below grade when earthquake, tornado and high winds are the primary relevant natural hazards. The floor level for the new vivarium may be selected based upon a desire to decrease the overall vulnerability already inherent in the program and the existing facilities. In our example, the reason that we selected the grade level as the optimum location for our new vivarium was that the majority of the research animals at our Midwestern university were already residing in below-grade locations that were vulnerable to flooding and we wanted an animal facility in which egress would be easy.

E. Incorporate Features into the Design so that the Vivarium can Remain Operational After a Disaster

It is important to remember that the structure of the vivarium must remain intact to provide shelter for animals and to allow the safe entry of animal-care staff in the immediate post-disaster period. The building's structural system should provide a continuous load path for the forces generated by the event to travel from their point of application to the foundation where they are resolved. Common structural lateral-force resisting systems include shear walls (concrete masonry units or reinforced concrete), steel-braced frames and special moment-resisting frames (concrete or steel). The reader is referred to Table 14-1 for reference sources that provide detailed information about construction mitigation techniques for common natural hazards.

The animal facility must have a protected, reliable source of emergency power that is able to support the essential services for the vivarium until local utilities are restored. There should be enough built-in redundancy in essential system components to ensure their operation after a disaster. The emergency power source and the utilities connections must be designed so that they can be easily interconnected. To allow more efficient delivery of emergency power to the vivarium, it might be desirable

Fig. 14-1 Electrical substations have been raised by placing them on concrete slabs and surrounding them with concrete curbs to protect them from flood damage.
Photo courtesy of FEMA/Dave Gatley.

to isolate the mechanical space for the vivarium's equipment from the other mechanical space in the building. The emergency generator and switch gear should be placed high enough in the building to prevent submersion in floodwaters (Figure 14-1). In earthquake-prone areas, the emergency generator should be installed near the base of the building and should be anchored to prevent sliding. In high-wind hazard areas, the generator should be surrounded by reinforced interior walls.

Standby equipment for critical systems must be carefully placed within the building and adequately reinforced so that it will remain functional. Utilities components must be protected from damage and installed in such a way that they will remain functional after the disaster. When possible, connections that support equipment should be flexible to minimize breakage and dislodgement. Electrical components should be installed above the design flood elevation in flood-prone areas. For minor internal flooding incidents, electrical systems can be protected by elevating components on concrete pads and surrounding them with curbs (Figure 14-2). For rodents, it may be more important to provide a system for standby cooling, as opposed to the default heating system that is typically installed.

It is very important to plan for animal safety when power is restored to the vivarium. Reheat valves and components should be installed so that they fail in the closed or "off" position. This will prevent the rapid heating of animal rooms that occurs when power is restored to the facility and these components default to "on." Rapid room overheating is one of the most common causes of sporadic animal deaths that occur during typical daily operating conditions in vivaria.

It is also critical adequately to protect the natural gas supply and distribution systems, since these components frequently cause devastating fires when dislodged or ruptured. When possible, flexible connections should be used to attach equipment to natural gas sources (Figure 14-3).

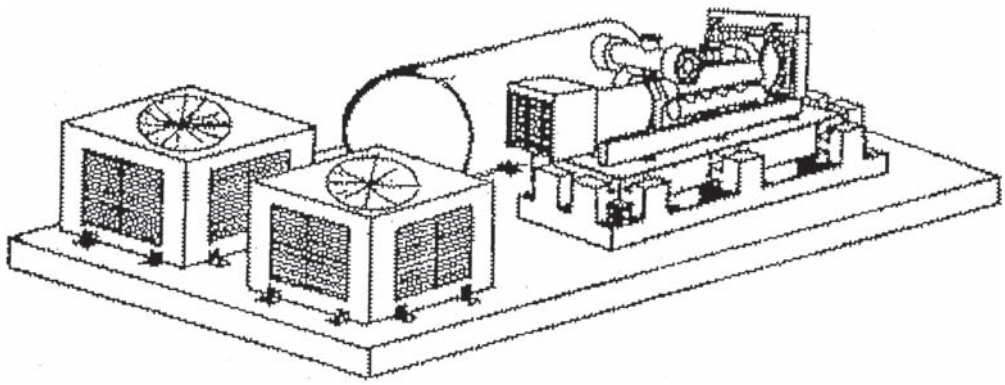

Fig. 14-2 Multi-hazard mitigation for mechanical equipment. The equipment is elevated on a concrete slab to protect it from flooding, and the bracing installed at the bases of the HVAC units and the placement of interconnected equipment on a single slab protects the equipment from damage during an earthquake.
Illustration courtesy of FEMA.

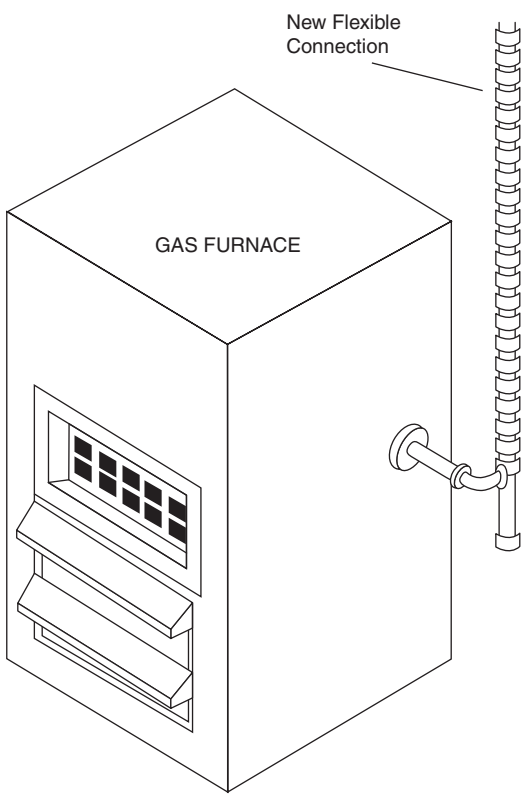

Fig. 14-3 Using a flexible connection between building equipment and the utility gas source decreases the likelihood that natural gas supply lines will rupture during a disaster. Ruptures in natural gas supply lines are common sources of devastating fires in disasters.
Image courtesy of FEMA ("How-to" Series Publications).

Components of the HVAC system can be protected from dislodgement and impact damage by installing cross-bracing or anchors. It is important adequately to protect these components when flood and/or earthquake are relevant natural hazards at the site (Figure 14-4).

Fig. 14-4 Utilities components and switches can be protected from flood damage by elevating them. Platforms can be attached to allow maintenance personnel to easily access these components.
Image courtesy of FEMA (Hazard Mitigation Series, Flood Hazard).

Plumbing components should be installed with sewer backflow prevention devices so that untreated waste is not discharged throughout the building if discharge lines become clogged or ruptured.

The interior components of the building also require attention to protect them from damage. In earthquake hazard areas, ceiling grids and light fixtures can be secured using anchors and cross-bracing. Moveable equipment, such as bookcases, computers and filing cabinets, should also be anchored. There are many products marketed for use in homes and businesses to prevent earthquake damage that also have direct application in the vivarium. In high-wind areas, tempered glass can be used in windows to improve their safety.

If the animal facility depends upon an elevator for access, it must remain functional. Elevators servicing animal facilities should have an emergency power supply. If a vivarium is located in a building where flooding is a potential hazard, animals should not reside below grade and the elevator should be

flood-proofed. This can be accomplished by installing interlocking controls and float switches in the elevator shaft, and by locating the electronic controls and hydraulic pump above the design flood elevation (FEMA, 1993).

VI. CONDUCT A SYSTEM-BY-SYSTEM FAILURE ANALYSIS

Design professionals should rigorously apply Murphy's Law (if it can go wrong, it will!) to the total building design concept to solidify design and operational responses to disasters. A simple and comprehensive failure analysis of the building and systems will yield design refinements, alarms and operational response plans. Examples to consider include the location of the electrical service and/or the emergency generator, the location of roof drains and/or wet utilities, the containment of internal water sources, and the presence and location of standby equipment for critical systems. Placing the vivarium, emergency generator and electrical switch gear in the basement of a building is foolhardy when a flood hazard exists at the site. Conversely, placing mechanical equipment on the roof of a tall building is unwise in an earthquake or hurricane hazard region. Roof drains and internal water sources should not be placed in such a way that the animal facility will flood if these components rupture. Alarm systems should be verified. From detailed examination of each system during building failure, the design team will gain an understanding of how the building should perform during a disaster. This information can help refine the design to eliminate problem areas. Most importantly, this information will help the building's owner and occupants to develop more effective operational emergency-response plans.

VII. COMMISSION AND THEN RECOMMISSION THE ANIMAL FACILITY

The new vivarium should be commissioned prior to initial occupancy to verify that all systems operate as designed. The animal facility should also be recommissioned on a regular basis to validate "in operation" condition. Commissioning will document settings and performance, fail-test systems and prove alarm conditions, and find deficiencies prior to an emergency. These procedures will train staff on what to expect during a real emergency, and help them to develop a response plan that is tailored to the level of performance expected from the building.

VIII. CONCLUSIONS

Research animals are living beings that often represent unique, irreplaceable models (such as genetically-engineered rodents that exist at only one location in the world). They represent a considerable investment, both in money and in humane considerations, and oftentimes the research in which they are used cannot be continued if they are lost. Hazard mitigation techniques are most economical when they are considered at the outset of the planning process, and a multi-hazard approach is the best way to arrive at the correct design for the new building. The planning team must remember that a specific building design or construction technique that is applied to protect against a specific type of natural hazard may either reinforce or conflict with one for a different type of hazard. It is important that the planning team for the new research building and vivarium recognizes the specific types of hazards that could be operable on the new building and learn how to mitigate their effects.

The desired level of performance, above and beyond the code-compliant minimum standards, needs to be determined after a careful evaluation of the increased construction costs is balanced against the likelihood that certain disasters could occur, the replacement value of the research animals at-risk, and the likelihood that the research program could continue to operate if the building and animals were lost.

IX. DEFINITIONS

Building code – building codes are city, county or state regulations that set forth the requirements and standards for construction, maintenance and occupancy of buildings. They are designed to provide for public safety, health and welfare. They prescribe the minimum acceptable standards for construction of a structure to mitigate against a defined hazard (e.g., fire or earthquake).

Design professional – design professionals include the architects, MEP (mechanical, electrical and plumbing) engineers and structural engineers.

Facility planning team – the facility planning team consists of representatives from the contracted architectural and engineering firm and those individuals who represent the building's owner. The building owner's team usually includes the vivarium's director, and representatives from environmental health and safety, maintenance and utilities, security, and fire safety.

Immediate Occupancy performance – a performance objective established during the design phase of construction in which overall damage to a building will be light following occurrence of the design disaster event (e.g., an earthquake hazard of a defined intensity). Non-structural and mechanical and electrical components remain secured and the utilities necessary for life safety systems are available.

Life Safety performance – a performance objective established during the design phase of construction of a

building which is intended to provide resistance to collapse during a design disaster event (e.g., an earthquake hazard of a defined intensity). The structure may lose a substantial amount of its original stiffness and strength, but the gravity-load-bearing elements provide some safety margin against collapse of the building. Structural and non-structural damage to the building is significant. The structure will likely not be safe for continued occupancy until repairs can be accomplished.

Redundancy – in building systems, redundancy refers to the duplication or repetition of a component or system in order to provide an alternate method to deliver an essential utility or service in cases when the primary delivery system or equipment fails.

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Chapter 15

Animal Isolation Cubicles

Jack R. Hessler and William R. Britz

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I. INTRODUCTION

"Animal isolation cubicles" are an animal facility design concept used to greatly increase flexibility for animal isolation within minimal space by subdividing animal rooms into small animal housing spaces, typically large enough to hold one standard-size animal cage rack. Figure 15-1 is a schematic of an animal room subdivided into animal cubicles. An early version of the design concept using the term "cubicles" was published by Reyniers (1943) in a book titled *Micrurgical and Germ-free Techniques*, in which Reyniers describes in detail the design and use of "baby cubicles" in Chapter IX 'The control of cross infections among limited populations. The use of mechanical barriers in preventing cross-infection among hospitalized infant populations.' Dolowy (1961) was the first to describe the basic configurations of animal cubicles as they are typically used today for isolating small populations of animals. Animal cubicles have been variously identified as "Illinois cubicles" since those described by Dolowy were at the University of Illinois at Chicago, "modified Horsfall cubicles" after isolators first described by Horsfall and Bauer (1940), "isolation cubicles" (Britz, 2003) and "animal cubicles." In this chapter they are referred to as "animal isolation cubicles," "animal cubicles" or just "cubicles." The need for animal isolation cubicles in the typical rodent centric research animal facility may have decreased with the increased use of micro-isolation cages (static and ventilated) for rodents. Ventilated racks may be a more cost-effective way to provide isolation for rodents than animal cubicles (Ruys, 1988). However, cubicles continue to be useful when housing of rodents in open-top cages and when multiple isolation spaces

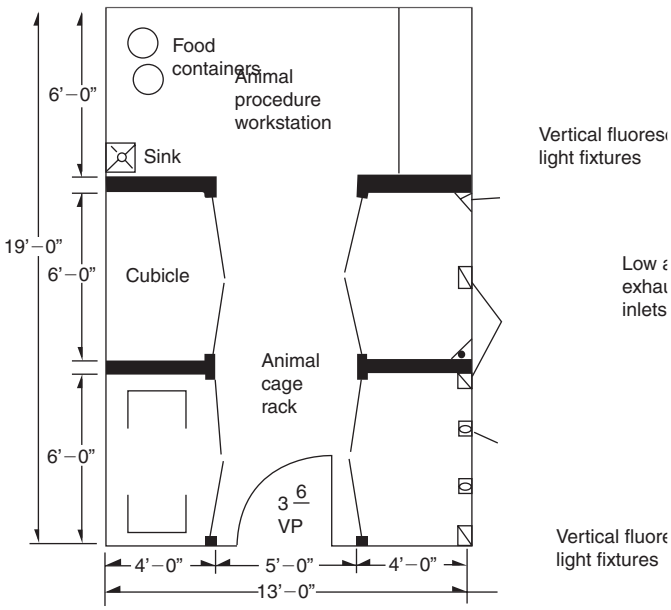

Fig. 15-1 Schematic of a small animal isolation cubicle room with four 4' × 6' cubicles, a 5'-wide aisle between the cubicles, an animal procedure area and a service area. Also illustrated are two options for the location of vertical wall-mounted lights, two options for the location of low air exhaust air outlets (could just as well be supply air inlets), and a crash guard to protect the air ducts and lights.

are required for housing small numbers of animals that need to be isolated for any reason, including animals in quarantine, those experimentally exposed to hazardous agents (even when the primary barrier is a micro-isolation isolation cage), isolation of small experimental groups, and for different environmental conditions such as light cycles.

Typically, animal cubicles have been used to isolate small animals (rodents, rabbits, cats, small primates, etc.) in cages on mobile cage racks. This type of cubicle is referred to as a "small animal cubicle." The animal cubicle concept has also been applied to housing larger animals (dogs, sheep, goats, pigs and even poultry) on built-in raised floors or in portable pens or cages rolled into the cubicle. This type of cubicle is referred to as a "large animal cubicle." Both are described in this chapter. Animal cubicles can be built in place, or prefabricated as a unit complete with all required architectural and engineering features ready to be integrated with the building systems. Both are described in this chapter. The use of animal isolation cubicles along with architectural and engineering features have previously been described in detail (Hessler, 1991, 1993; Britz, 2003).

II. ISOLATION

For the purposes of this chapter, the term "isolation" is defined as preventing cross-contamination between animal populations housed in animal isolation cubicles within an animal room. Cross-contamination may occur by the airborne route or by physical contact. Since preventing physical contact is largely a management issue, the primary focus in this chapter is on using animal cubicles to prevent airborne cross-contamination.

Animal cubicles as generally designed and used do not provide perfect isolation. The following describes why this is so and why, in spite of this fact, they are still effective for isolating small populations of animals.

Most cubicles are designed for containment, with the air pressure in the service aisle between facing cubicles positive to all the cubicles in the room. Balancing ventilation with the cubicle positive to the aisle theoretically reduces the opportunity for cross-contamination but increases the exposure of personnel to animal allergens and, of course, is not suitable for containment of infectious or other hazardous agents. Even when the relative air pressure in the aisle is positive to the cubicle, this pressure relationship breaks down when a cubicle door is opened, and the potential exists for air from that cubicle to enter the aisle space outside the cubicles. Since the aisle is still positive to the other cubicles in the room, the potentially contaminated aisle air may enter the other cubicles. For this reason isolation is less than perfect, making it reasonable to question the effectiveness of animal cubicles for controlling airborne contaminates. Extensive experience over many years in many facilities indicates that cubicles do effectively prevent airborne infectious agents from spreading between cubicles in the same room. At least one published study (White *et al*., 1983) has documented the same, although this study involved a limited number of infectious agents. Reasons that cubicles provide an adequate level of isolation for most situations include the following:

- The window of opportunity for cross-contamination between cubicles is limited to the relatively brief time when a cubicle door is open.
- Depending on the ventilation pattern selected, exposure of the animals to infectious agents in the potentially contaminated air from the aisle can be mitigated by directing the aisle air directly toward the cubicle exhaust (see Ventilation, Options 2 and 3, below).
- There is substantial dilution of airborne contaminants with large volumes of fresh unrecirculated air ventilating the aisle and cubicles. To infect an animal by the aerosol route requires either a highly virulent organism, a high concentration of the organism, or both.
- Infectious agents of concern may not readily spread by the aerosol route, and cross-infection between cubicles is more likely to occur via fomites, including human hands.

III. PROS AND CONS OF ANIMAL CUBICLES

A. Pros

- Animal cubicles maximize the number of animal housing spaces that can be provided for isolating small groups

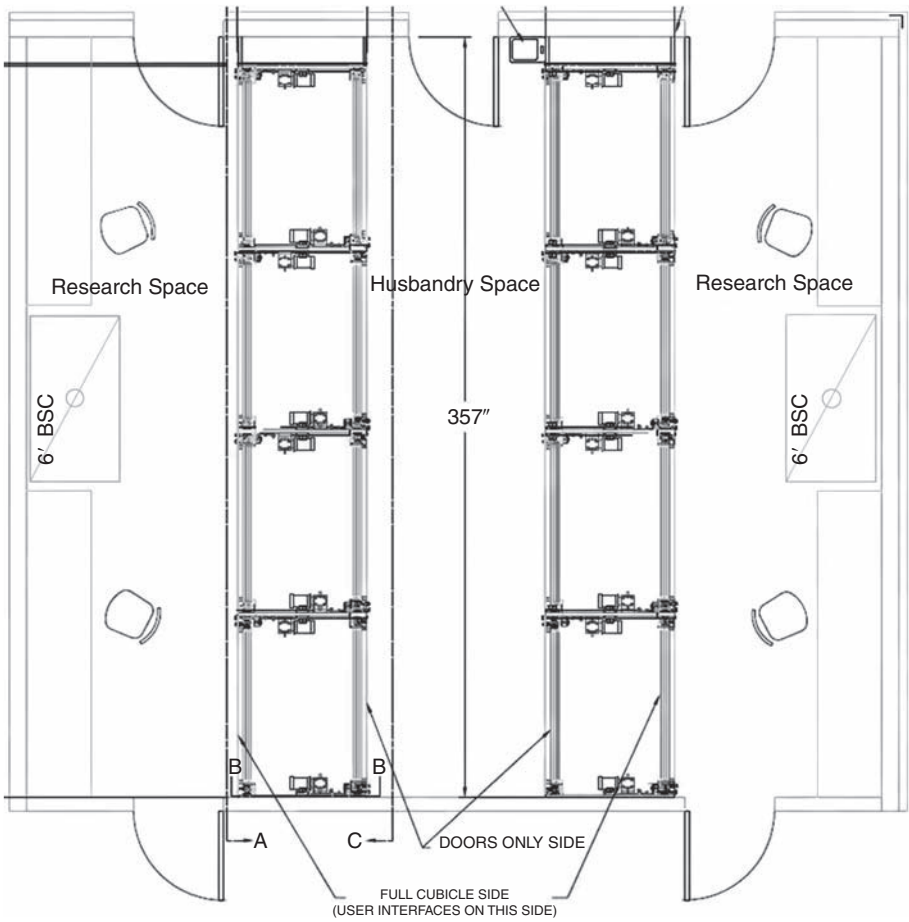

Fig. 15-2 Animal cubicles that open from both sides.

of animals within a given amount of animal housing space.

- For new construction or renovations, animal cubicles can be used to address the problem of what to do when a facility has sufficient animal housing space but too few spaces to provide the necessary separation of animals by species, source, microbiological status or project, or when experimentally exposed to biological, chemical or nuclear hazards. Multiple species may be housed within different cubicles within a cubicle room.
- When small isolation spaces are required, large rooms divided into animal cubicles allow for more efficient use of space than do multiple small rooms, because the larger the rooms in a facility, the smaller the ratio of circulation space to animal housing space and vice versa.
- Animal cubicles provide an additional level of "barrier" or "containment" between the animals and the corridor to the room.
- Investigators with small numbers of animals tend to like animal cubicles because they provide a degree of isolation and clear separation of their animals from other animals in the facility that otherwise would not be practical or even possible.

B. Cons

- Animal cubicles decrease the maximum animal housing capacity in a given area by approximately 10–20 percent.
- The typical arrangement with animal cubicles lined up along a wall makes cubicles best suited for single-sided racks. Double-sided racks are not practical because they must be removed from the cubicles to observe the animals on the back side, which may be considered a serious impediment to assuring animal welfare. Remediation for this problem includes using carousel-type rodent racks or double-sided cubicles (Figure 15-2), but double-sided cubicles require additional aisle space.
- A cubicle room is relatively inflexible in terms of converting it to an open room in that it requires significant renovation. Renovation requirements are less extensive with prefabricated cubicles than with built-in-place cubicles.
- Isolation is imperfect. The previous section elaborated on why this is not a significant limitation with the exception of airborne organisms that are either aerosolized in high concentration or are highly virulent, or both.

IV. BUILT-IN-PLACE ANIMAL CUBICLES

A. Small Animal Cubicles Built in Place

1. *Configuration of cubicles and rooms with small animal cubicles*

There is no set size for animal cubicles, but a common size is approximately 4' deep by 6' wide, large enough to hold one 5'6"-wide by 30"-deep animal cage rack. However, it is critical that great thought be given to cubicle sizes at the outset of planning to ensure that the cages and equipment to be placed in them will work well in them. Larger cubicles, e.g., 7' × 7', that can hold two racks and/or in which a person could perform simple tasks with the doors closed may be better for some applications. The deciding factors in determining the minimum size of the cubicles and the number of cubicles in a room are the size of the cages or cage racks to be put into the cubicle, the size of the animal room, and the amount of service and animal-use space desired in the room. The width of the aisle space between facility cubicles is also a factor, but it is highly recommended that it not be less than 5′ wide. Figure 15-1 illustrates the layout of an animal cubicle room with four cubicles, a service area for a sink, feed containers and a mop bucket, and an animal procedure workstation, which could be a biosafety cabinet. It could just as well have six or any even number of cubicles; however, at some point additional animal procedure space may be required, especially if multiple investigators will be housing animals in the room. Figure 15-3 illustrates three different cubicle and cubicle room configurations, including one with 7' × 7' cubicles and one with 3' × 6' cubicles. A practical approach to determining the cubicle depth is to subtract 5' from the width of the room and divide it by 2 to get depth of the cubicles. If that depth is not enough for the cages to be used in the cubicle after taking into consideration the depth of the cage rack, and interior cubicle features such as air ducts, lights and wall protection, then the room is too narrow to have cubicles on both sides of the room. Of course, cubicles can be lined up only on one side of the room, but this arrangement is less efficient in terms of space per cubicle. Cubicles may also be double-sided, arranged with doors on both sides of the cubicle (see Figure 15-2).

2. *Architectural Features*

a. Construction Materials and Finishes

Materials and finishes that are being used for animal rooms in the facility are generally suitable for small animal cubicles. Divider walls between cubicles may be the same as the room walls; however, if the facility walls are cement block then steel-studded walls with high impact resistant panels could be considered for the side walls of the cubicles. The hollow walls offer the advantage of providing space to bring air plenums down to the floor level. In new construction, the divider panels are typically built before the floor covering and coved base is installed. With prefabricated cubicles, this detail needs to be coordinated with the cubicle supplier. The walls of the cubicle, especially the back wall, should be protected with guard rails. The side walls could also have guardrails if the cubicles are wide enough to accommodate the cage racks with the rails in place.

b. Doors

The door to the animal isolation cubicle room should be identical to the standard animal room door for the facility. The cubicle doors should have full-panel glazing to facilitate observing the animals without opening the doors. Occasionally, cubicles require light control independent of the cubicle room. Options to meet this need include the following:

1. Using red-tinted glazing carefully specked to block out light in the visible range for rodents but allow enough light transmission in the red range to provide visibility for humans is an option on cubicle doors (“Rose-Chocolate 3" from Solar Graphics and “Vivarium Red” from Aegis Applied Films; see Chapter 33 in this book for more details).
2. Light through the clear glazing can be blocked in some manner, for example by covering it with black polycarbonate panels.
3. Doors may be installed without a view panel.

The door opening should be no less than 4–6″ wider than the racks that will be used inside the cubicle. The height of the cubicle doors should be the same as the animal room door unless there is a degree of certainty about the height of the racks to be used in the cubicles. Many styles of doors are used for animal cubicles, including hinged doors, multi-panel (typically three or four panels) vertical sliding overhead stacking doors, and horizontally sliding doors. Vertical sliding overhead stacking doors are probably the most common, but hinged doors are also frequently used. Horizontally sliding doors are rare and are not described here.

Hinged Doors Figure 15-1 is a schematic of an animal cubicle room showing hinged doors and Figure 15-4 is a photo of a cubicle with hinged doors. Typically, hinged doors for animal cubicles consist of a pair of aluminum frame doors with full-panel acrylic or safety-glass glazing mounted on a doorframe consistent with what is being used for the animal room doors. Options include mounting a single door on each side of the doorframe or a pair of bi-folding doors on one side of the doorframe. The door hardware should include: hinges that allow a 180° swing into the aisle to allow the doors to rest flat against the adjacent closed cubicle doors when possible so as not to block the aisle; a grab bar mounted horizontally across the door 36″ from the

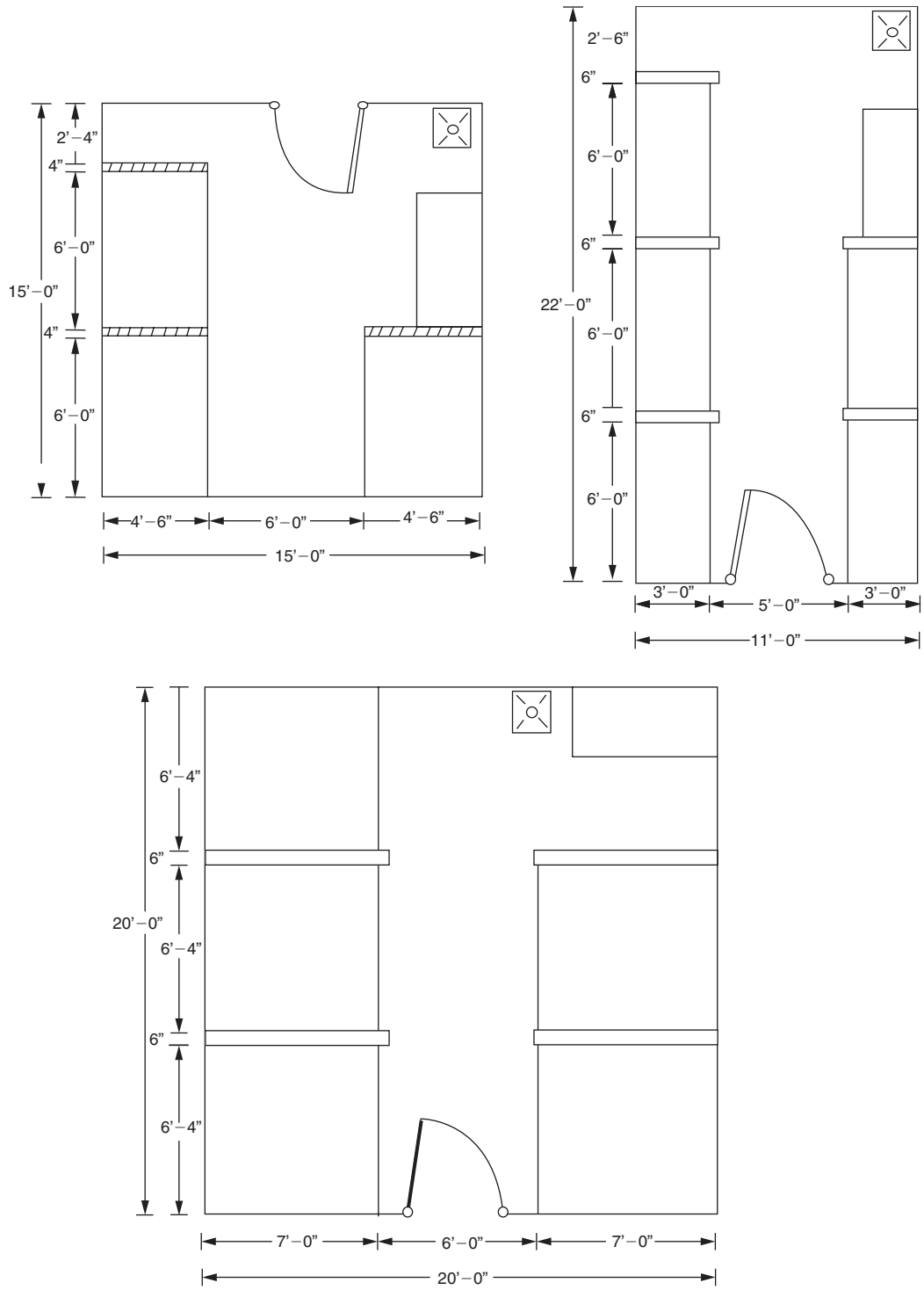

Fig. 15-3 Examples of three different-sized rooms (15′ × 15′, 22′ × 11′ and 20′ × 20′) subdivided into three different-sized cubicles (3′ × 6′, 4′ × 6′, 7′ × 7′) with corridors varying from 5′ to 6′.

floor to protect the door and serve as a door handle, taking care that the grab bar doesn't interfere with the 180° door swing; and heavy-duty adjustable roller-type friction latches at the top of each door. Drop bottoms may also be desirable. Depending on the ventilation pattern used, a ventilation panel may be required either at the bottom or top of the door. The doors should have flush-mounted end-plate covers and be fully sealed to facilitate sanitation and eliminate harborage sites for insects and vermin. The doorframes should have hospital stops to facilitate floor sanitation.

Fig. 15-4 Small animal cubicle with hinged doors and vertical mounted fluorescent lights in back corners.

Vertical Sliding Overhead Stacking/Telescoping Doors With vertical stacking/telescoping door systems, the opening to the cubicle space is subdivided by a set of three or four interlocking fully glazed door panels. Figures 15-5, 15-6 and 15-7, which are schematics primarily intended to illustrate three options for ventilating animal cubicles, also illustrate three-panel vertical stacking doors to each cubicle. Figure 15-8 is a photograph of a built-in-place cubicle with open vertical sliding doors. With vertical telescoping door systems, the opening to the cubicle space is subdivided by a set of three or four interlocking "glass" panels. These doors may be opened and closed either manually or by an electronic motor. Operationally, the doors are designed to "telescope." As the doors are lifted, the lower doors successively lift the next door. When fully opened, the set of doors become "stacked" and occupy a small space immediately above the ceiling of the cubicle space. As the doors are lowered, the lower doors successively pull the next door down. Better door designs include a mechanism that pulls the doors tight when closed, thus creating a seal across each door intersection. The bottom edge of the bottom door may include a soft gasket to allow the door to seal fully to the facility floor. Thicker, softer gaskets may be needed, depending on the quality and levelness of the facility floor.

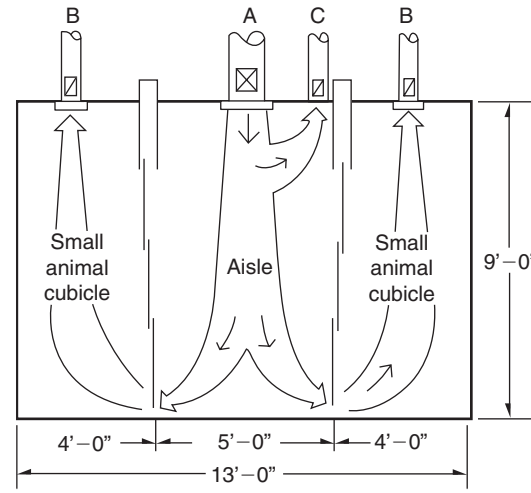

Fig. 15-5 Option 1 ventilation pattern for small animal cubicles. A, building air supply; B, to building exhaust from animal cubicles; C, to building exhaust from animal procedure area. Also illustrated is a three-panel vertical stacking door for each cubicle.

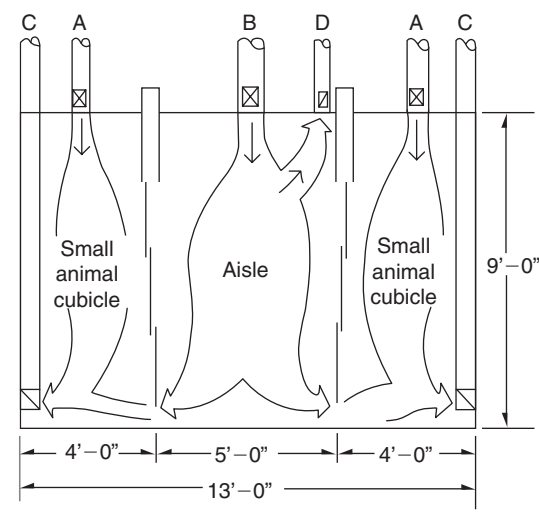

Fig. 15-6 Option 2 ventilation pattern for small animal cubicles: A, building air supply to cubicles; B, building air supply to aisle; C, to building exhaust from animal cubicles; D, to building exhaust from animal procedure area. Also illustrated is a three-panel vertical stacking door for each cubicle.

The glass panels can be either a safety plated glass or a clear polycarbonate (e.g., Lexan™). The "glass" panels are mounted in stainless-steel framework that provides the interlocking features of the doors. Polycarbonate materials are significantly lighter weight and require less framing materials. These two factors allow polycarbonate systems to be significantly less expensive than their glass counterparts.

The glass doors are mounted in a staggered track system in a pair of door columns or door-jambs. The jambs are typically fabricated with stainless-steel structures and high-density polyethylene (HDPE) tracks. The jambs contain the inner workings

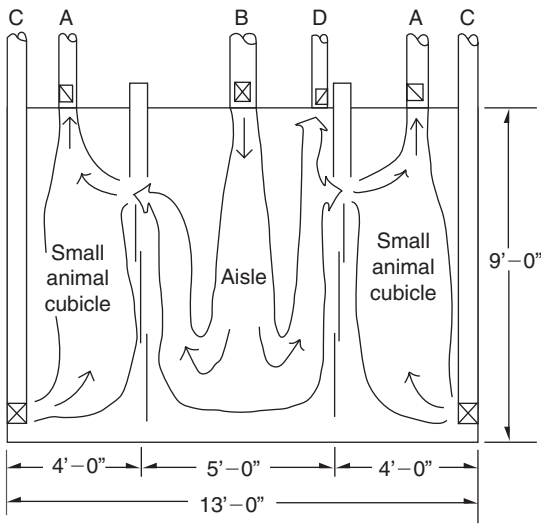

Fig. 15-7 Option 3 ventilation pattern for small animal cubicles: A, to building exhaust from animal cubicles; B, building air supply to aisle; C, building air supply to cubicles; D, to building exhaust from animal procedure area. Also illustrated is a three-panel vertical stacking door for each cubicle.

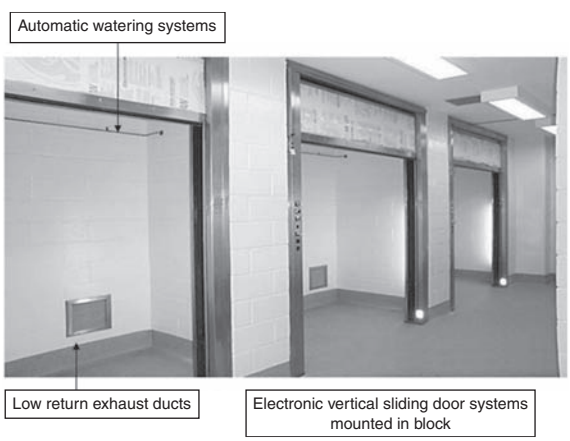

Fig. 15-8 Built-in-place masonry block wall cubicles with open prefabricated vertical sliding doors that telescope up into the header.

of the door-operating system – a series of cable and counterweights for manual doors, or chain drive and counterweight in automatic doors. When selecting cubicle systems, door columns that have simple access methods can be valuable for long-term maintenance and routine cleaning.

In manually-operated systems, each door panel is individually counterweighted. The counterweights are connected by a stainless-steel aircraft cable that is slung over a pulley system. As a matter of experience, these cable systems are known to be problematic and require frequent replacement. When the doors are fully closed, a toe-lock system is typically used to hold the doors in the closed position. To open the doors, the toe-locks must be opened on both sides of the cubicle doors. The doors are then simply lifted/pushed to their fully open position. When closing, care must be taken by the operator to ensure that the toe-locks are fully engaged, otherwise the door system may not be fully sealed.

In electronically-operated systems, the bottom door panel is generally connected to a drive chain. The drive chain is connected to an electronic motor mounted above the cubicle space. The doors are opened and closed via push button, typically located on one of the door-jambs. The electronic system senses and controls the doors to ensure that they are either fully open or fully closed. The electronic system is set to ensure that a full seal is created with the facility floor and at each door intersection each time the doors are operated. Safety features include:

- push-and-hold operator buttons, where the operator must hold the door-up or door-down buttons to operate the doors; this mitigates the possibility of the operator being under the door during operation;
- infrared sensors, where an infrared beam and sensor system us used to identify blockages and prevent the doors from closing, similar to the safety sensor on garage doors;
- interior operator buttons, where a secondary set of door operation buttons is mounted inside the cubicles space;
- manual override, which is a method to disengage the electronic drive motor to allow the doors to be lifted or lowered manually.

Pros and Cons of Each Door Style *Vertical sliding overhead stacking doors:*

- permit opening of the doors with minimal consideration for the location of equipment (e.g., cage racks) in the aisle;
- create minimal air turbulence when being opened;

BUT

- cost several times as much per opening as hinged doors;
- impede sanitation and vermin control because of the guide channels, the concealed spaces for the opening and closing mechanism;
- are mechanically more complicated and thus require more maintenance to keep them operating smoothly or at all;
- have thicker frames to accommodate the multiple door panels, thus taking up more valuable space;
- require overhead space that may not be available, especially in renovation projects. The less the overhead space, the more panels required and the more panels, the thicker the doorframe.

Hinged doors:

- allow for easier, more complete sanitation and vermin control;
- are easier and faster to open, even when compared to properly installed and function vertical sliding doors (motorized vertical sliding doors are easier to open but not necessarily faster);
- require virtually no mechanical maintenance;

- are relatively free of structural impediments to sanitation and vermin control;
- are readily available from numerous suppliers;

BUT

- intrude into the aisle space while being opened, thus requiring the operator to plan ahead in terms of the equipment placement in the aisle;
- create air turbulence when being opened, thus causing air from the cubicle to mix more readily with the aisle air.

3. *Engineering Features for Small Animal Cubicles*

a. HVAC

Ventilation Pattern Options There are multiple options for ventilating small animal cubicles. The following describes three of the most common:

Option 1. Fresh air, supplied from the ceiling of the aisle between the cubicles, flows under the cubicle doors, through the cubicle and is exhausted at the ceiling of the cubicles (Figure 15-5). This is the ventilation that was most commonly used for animal cubicles constructed in the 1960s and 1970s. They were generally considered satisfactory, and many are still in use today. It is the least expensive to construct, the simplest to balance, and the relative air pressure in the aisle is guaranteed to be maintained positive to the cubicles when the cubicle doors are closed. Because of concerns for cross-contamination between cubicles when a cubicle door is open and the aisle air is potentially contaminated, Options 2 and 3 below became more commonly used, especially in biohazard containment facilities.

Option 2. The primary cubicle ventilation is fresh air supplied at the cubicle ceiling and exhausted near the cubicle floor. The aisle is ventilated with fresh air supplied at the ceiling of the aisle and exhausted either at the ceiling in the animal procedure area or under the cubicle doors – or through a vent at the bottom of the door if the doors are equipped with drop bottoms – into the cubicle, where it is exhausted near the floor of the cubicle (Figures 15-6 and 15-9). This pattern is consistent with the dogma that existed for many years, to supply high and exhaust low to best control airborne contaminates. In addition, with this configuration, the aisle air theoretically passes through the cubicle without significantly mixing with air ventilating the animal cages in the cubicle.

Option 3. This option is identical to Option 2 except that air in the cubicle is supplied near the floor of the cubicle and is exhausted at the ceiling, and the air from aisle passes into the cubicle near the ceiling through a vent at the top of the door or above the door and then is exhausted at the ceiling (Figure 15-7). The effectiveness of this option is supported by a computational fluid dynamics CFD study modeling animal cubicles. The results of the study indicate that air supplied at the floor and exhausted at the ceiling more effectively removes airborne contaminants from animal cubicles than when air is supplied at the ceiling and exhausted at the floor (Curry *et al*, 1998). Of course, the actual flow patterns will vary according to the items inside the cubicle at any given time.

Fig. 15-9 Back corner of small animal cubicle showing a triangular air duct (in this case an exhaust duct with a filter, but it could be designed as a supply air duct) extending from the ceiling to the floor with a fluorescent light fixture mounted on it.

Option 1 is the least expensive to build, because it does not require low air ducts and is the simplest in that it is self-balancing with regard to keeping the aisle positive to the cubicles. It is also the most efficient in terms of handling heat loads in the cubicle, because the air from the aisle is not short circuited to the exhaust duct inside the cubicles. This is also a disadvantage is that potentially contaminated air is directed past animal cages. If animals are housed in micro-isolation cages, this should not be a concern. Options 2 and 3 at least partially address the primary concern of Option 1 by directing the air from the aisle to the exhaust duct located either at the bottom or the top of the cubicle. While there is some degree of

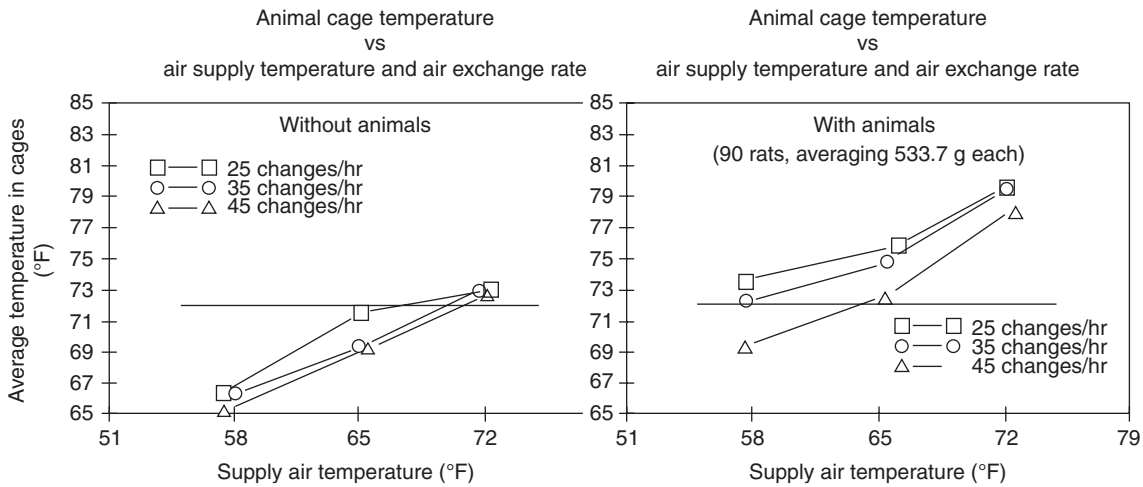

Fig. 15-10 Average animal cage temperatures versus air supply temperature at three different air exchange rates in an empty animal cubicle and an animal cubicle housing a maximum number of rats.

mixing with air in the cubicle, most of it is exhausted without passing by the animal cages. There are no well-documented data to support Option 2 or 3, other than the CFD study already noted, that suggest that Option 3 may be best, possibly because warm air rises, although Option 2 seems to be the one most commonly used.

Temperature Control and Ventilation Requirements Temperature control in small animal cubicles is problematic because of the small space with a highly variable heat load (a few mice versus maximum capacity of rats). Individual temperature control of each cubicle with a terminal reheat and a thermostat is costly as well as problematic. For example, if the heat load in the cubicle is high, calling for cool air to be supplied to the cubicle, the animals close to the supply diffuser will be exposed to cool air before it has a chance to mix in the small space. There are ways to address this problem, but they increase the cost. The problem can be satisfactorily addressed by designing the cubicle room with a single terminal reheat and thermostat sensing temperature in an exhaust air duct common to all cubicles in the room. Given that a cubicle may be housing only a few mice generating negligible heat, the air temperature delivered to that cubicle and all the cubicles must be delivered at a comfortable temperature for mice (e.g., 72°F, or 22.2°C). This means that the heat load in the cubicle with a maximum heat load must be handled by dilution with relatively warm air rather than cool air. Given the small volume of air in a cubicle, heat load dilution can only be provided by ventilating the cubicle with volumes of air greater than the classic 10–20 changes per hour (cph). The 36–72 cubic feet per minute (cfm) of air required to produce a theoretical air exchange rate of 10–20 cph in a 4′ × 6′ × 9′-high cubicle is not sufficient to maintain a reasonable temperature in a cubicle housing the maximum capacity of rats. Rats are chosen as an example because, given current housing space standards, they produce the highest heat load in a given square foot of animal housing space. Figure 15-10 is a graph of data from a study based on 90 rats, averaging 534 grams each, that were housed in wire-bottom cages on a 5-shelf rack with 6 cages (3 pairs back to back) per shelf inside a 4′ × 6′ × 9′ cubicle with full panel glass doors, the temperature outside the glass doors being 72°F. Temperature was measured inside 18 cages on the rack, 6 each in the top, middle and bottom shelves of a 5-shelf rack. The graph plots the average temperature in the three cages against three different supply air temperatures (58°F, 65°F, 72°F) at three different air exchange rates (25 cph (90 cfm), 35 cph (126 cfm), and 45 cph (164 cfm)). The graph shows that when 72 F-air was supplied to the cubicle at a rate of 35 cph (126 cfm), the average cage air temperature was approximately 79°F (a ΔT of 7°F) and when the 72°F air was supplied at the rate of 45 cph, the exhaust air temperature was approximately 77°F (a ΔT of 5°F) (Hessler, 1991). While 79°F is within *Guide* (ILAR, 1996) standards for all species except rabbits, it is pushing close to the maximum temperature of 80°F recommended for rodents. Considering the very high animal-produced heat load in this study an exchange rate of 35 cph (126 cfm) would be adequate most of the time, and if a lower supply air temperature of, say, 70°F were selected then 35 cph would be adequate even with the highest heat load. Of course, there is a limit to how low the supply air temperature can be, because it will be the temperature in the near empty cubicle housing, for example, a few mice.

Based on this, if air temperature is to be supplied to all cubicles at the same temperature, e.g., 72°F, an air exchange rate of between 126 cfm and 164 cfm is recommended for each cage rack in the cubicle regardless of the size of the cubicle. A fresh air exchange rate of 8–10 cph in the aisle space of the cubicle room is recommended to handle the heat load transferred from the cubicles, and to control contaminants that enter the aisle when cubicle doors are opened.

b. Lighting

Fluorescent ceiling lights provide the primary room lighting, fluorescent light fixtures centered between each pair of facing cubicles and in the animal procedure area providing approximately 30 foot-candles of light 36″ from the floor inside the cubicle close to the closed door. Given the close association of the back and side walls with the cage racks, in addition to shading from the front wall above the doors, the lights in the ceiling of the aisle often provide inadequate lighting to observe the animals in cages at the lower levels. For this reason, two one- or two-tube vertical-oriented fluorescent light fixtures may be mounted either at back or front of the cubicle. If mounted in the back, they are either located in the back corners or spaced to divide the back wall into equal thirds. If space is provided, the light fixtures can be mounted in the front inside corners of the cubicle. If the vertical wall-mounted lights are provided, the light level 6″ from the light diffuser should not exceed 30 foot-candles.

Lighting for each animal cubicle room must be independently and automatically controlled, preferably centrally with a microprocessor control system. Locally-mounted digital light timers are a second-best choice. The ceiling and cubicle lights in each room may be controlled together; however, consideration should be given to providing the lights in each cubicle with a manual switch that allows them to be turned off should they not be needed or it is considered that there is too much light for a given situation. In some instances it may be necessary to maintain light cycles inside a cubicle independent of the lighting in the room or other cubicles in the room. In this case, the cubicle lighting would need to be controlled independent of the room lighting and other cubicles.

c. Power

A 120-volt duplex receptacle should be provided on a side wall of each cubicle 7 feet off the floor. In addition, a 120-volt duplex receptacle should be provided on the wall above the animal procedure workstation. If there is not a built-in animal procedure workstation, the receptacle could be used to power a mobile biosafety cabinet that may be parked in the same area. All power outlets should have watertight covers.

d. Communication

Data ports may be required at the animal procedure workstation and in some animal cubicles, although, wireless technology may nullify the need for data ports. Of course, systems used to control and/or monitor the cubicle environment will require a means of communication.

e. Plumbing

All cubicle rooms should have the same sink as other animal rooms in the facility. A floor drain in the aisle and automatic watering lines in the cubicles may or may not be required, depending on the standard operating procedures to be used.

B. Built-in-Place Large Animal Cubicles

The same sufficient space but insufficient spaces problem often exists for the large animal research species. The inflexibility of the traditional dog room is even more of a problem than ever with the declining use of dogs and increasing use of pig, sheep and goat models in biomedical research. The large animal cubicles are also useful for housing other species, such as chickens and other birds, and non-human primates. The primary difference between large and small animal cubicles, besides size, is that they are designed to accommodate routine sanitation procedures involving the daily use of a hose, including sloped floors and drain troughs. Figures 15-11 and 15-12 illustrate two layouts for large animal cubicle rooms that differ with respect to floor slopes and drainage.

1. *Configuration of Large Animal Cubicles*

There is no ideal or standard size for large animal cubicles. For example, they may be designed as single-pen size cubicles (e.g., 5' × 5' or 4' × 8') or larger cubicles subdivided with multiple pens. Like small animal cubicles, the width of the aisle between facing cubicles should be a minimum of 5'. Figure 15-11 illustrates a 24' × 30' animal room subdivided into five 9' × 9'8" cubicles, and an animal procedure area with each cubicle subdivided into two or three pens. The floors in this room slope toward 6" flush drains in the back corners of the cubicles. Figure 15-12 illustrates two adjacent 22' × 25' rooms with a 2'5" service area between and on the sides of both rooms. The 8"-wide drain trough in the service area receives wastewater from hosing down the adjacent animal cubicles. The service area also serves as the exhaust air plenum for the adjacent cubicles. The rooms are subdivided into various sized cubicles, with the smallest being approximately 8' × 12' and the largest 8' × 16'. The cubicles are designed to be further subdivided into 4' × 8' pens. Figure 15-13 illustrates a "large animal suite" with five animal rooms subdivided into "large animal cubicles."

The animal procedure area is equipped with a wall-mounted sink, a wall-mounted examination table and a wall-mounted counter top with over-the-counter and suspended under-the-counter case work (Figure 15-14). All are designed to facilitate sanitizing the floor by hosing it down into the drain trough in the adjacent service area.

The sides and back of each cubicle are solid. The front of the cubicles at the aisle is formed by full panel glazed doors. The back wall of the cubicle rooms illustrated in Figure 15-12 is raised approximately 8″ off the floor to provide passage to the drain trough in the center of the service area as the pens are flushed with water. Attached at the bottom of the back wall inside

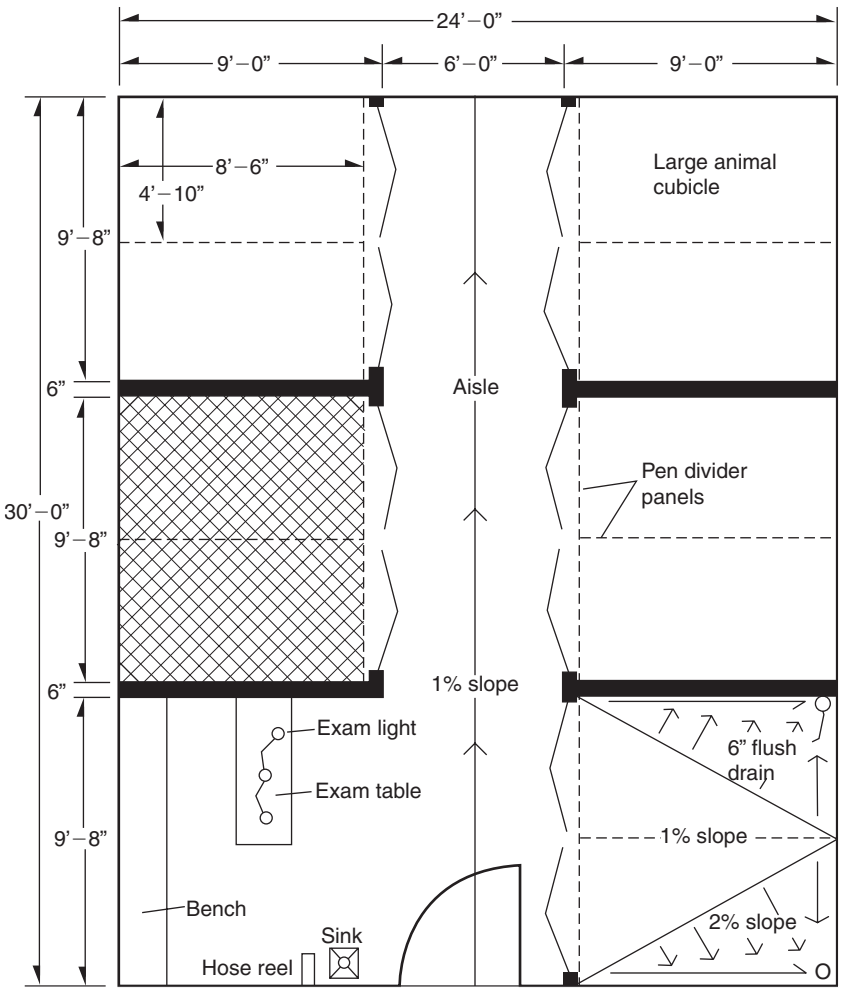

Fig. 15-11 Schematic of a large animal cubicle room subdivided with five 8′6″-deep × 8′-wide cubicles, with each cubicle divided into two 4′-wide pens. There is a 6′-wide aisle between facing cubicles, and an animal procedure area in place of one of the cubicles. Also illustrated are an example of a cubicle with a fixed raised floor and the location of the two floor drains and sloping floors designed to facilitate daily hosing of the floors under the raised floors. The pens could just as well be used with portable pens rolled into them.

the service area is a stainless-steel flashing extending to within 2″ of the floor and slanted slightly toward the drain trough. This reduces backsplash and splashing of waste water into the cubicles across the service area when the cubicles are being flushed with a hose. Suspended above the center of the trough is a splash panel to prevent water from splashing across the trough into the next room (Figure 15-15). The space under the back wall also serves as an air passage for exhaust air into the exhaust plenum – i.e., the service area.

There are many options for providing pens inside the cubicles. They may be built-in or mobile pens, but, either way, they should have appropriate raised floors. Figure 15-16 illustrates raised floors made from vinyl-coated expanded metal and fiberglass T-bar slats. Mobile pens could have the same raised floors. Of course, large animal cubicles are not limited to housing large animals. Figure 15-17 shows large animal cubicles being used to house birds. In addition, standard animal cages could be placed in the cubicles to house any species appropriate for the cage.

With portable pens or cages, consideration needs to be given to the relatively steep slope of the floors inside the cubicles, designed to facilitate daily sanitation with a hose. If portable pens or cages are to be used, one solution is to slope the floor less and another is to raise the height of the back wheels to adjust for the floor slope. Within each cubicle room is an animal procedure area equipped with a sink, an examination table and an overhead examination light.

2. *Architectural Features of Large Animal Cubicle Rooms*

a. Construction Materials and Finishes

Walls The walls of large animal cubicles have to withstand daily exposure to pressurized water spray and, if they are to serve as the sides of the pens, direct exposure to the animals. Some species (e.g., dogs and pigs) are capable of destroying most wall coatings. Glazed structural block with epoxy or furane grout (~1/4″ of the exposed surface) holds up well in this environment. Of course, stainless steel also works well, as may some carefully selected composite panels. Painted masonry walls are not advised.

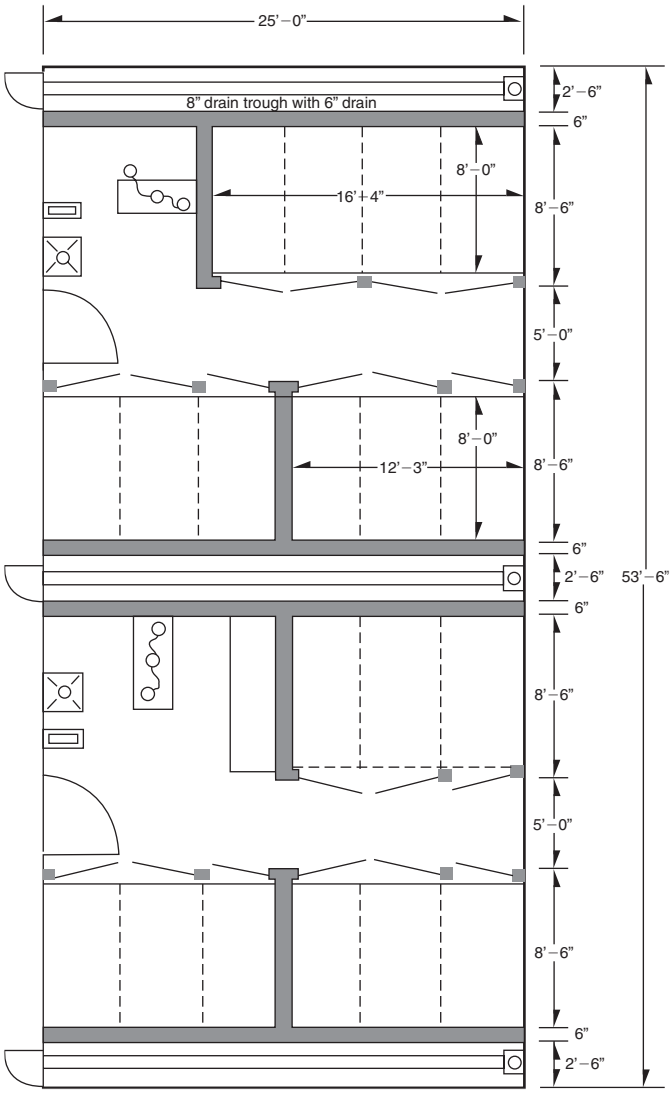

Fig. 15-12 Schematic of two large animal cubicle rooms illustrating an alternative drainage system in which floors are sloped from a high point in the center of the aisle to a drain trough located in the center of a 30″-wide service room immediately adjacent to back walls of the cubicles.

Ceilings The ceilings also need to be water resistant. Since they are not exposed to water spray every day, epoxy-coated water-resistant green board often proves satisfactory, but selected water-resistant composite materials that don't require painting would be a more certain bet. See Chapter 30 of this book for suggestions.

Floors While obvious, it cannot be overemphasized; the floors must slope to drains. The functionality of any facility such as this depends on it. The floors of the large animal cubicle rooms illustrated in Figure 15-11 are designed to slope toward 6″ flush drains in the back corners, with the floor sloped at a 1 percent grade, as illustrated. If constructed as drawn, it will function well because of the small size of the area; however, as a general rule, when a water hose is to be used for daily sanitation to remove a significant amount of solid waste, it works best when drainage is designed to flow toward a drain trough as opposed to a circular drain. The floors of the large animal cubicle room illustrated in Figure 15-12 are designed to slope as follows: the floors slope from the animal room door to the back of the room at a grade of 1 percent, as do the floors of the service area; starting from a crown in the center of the aisle between cubicles the floor slopes at a grade of 2 percent toward the drain trough in the center and running the length of the service space in back of the cubicles. The bottom of the drain trough slopes at a 2 percent grade from the corridor door opening into the service aisle to the other end of the trough into a 6″-diameter flush drain. The floors and drain troughs are then covered with a durable seamless coating (see Chapter 30 of this book for suggestions).

Doors Figures 15-11 and 15-12 are schematic drawings and Figure 15-18 is a picture showing large animal cubicles with hinged doors that open into the aisle. The specifications of the doors are identical to those described for small animal cubicles, with the exception that some consist of pairs of bi-folding cubicle doors. This allows for an unobstructed opening for the nearly 10'-wide cubicle when the doors are open. The space between the bottom of the door and the floor is determined by that necessary to make sure the opening door clears the floor as it slopes up to the center of the aisle. Of course, vertical sliding overhead stacking doors could also be used.

3. *Engineering Features for Large Animal Cubicles*

a. HVAC

Ventilation Pattern For the cubicles illustrated in Figure 15-11, fresh air is supplied at the ceiling in the aisle and inside the cubicle via a linear diffuser near the door. Air from the aisle is exhausted under the cubicle doors and into the cubicles. Air from the cubicles is exhausted at the ceiling in both back corners of the cubicle. For the cubicles illustrated in Figure 15-12, fresh air is supplied at the ceiling in the aisle between cubicles and in each cubicle via a linear diffuser running the width of the cubicle. Air from the aisle is exhausted under the cubicle doors and into the cubicles. Air from the cubicles is exhausted under the back wall of the cubicle into the service area, which also serves as the exhaust air plenum for the connected room or rooms. Air is exhausted from the plenum at the end of the plenum opposite the service room door.

Temperature Control and Ventilation Requirements Temperature control of large animal cubicles is relatively simple as compared with small animal cubicles because the cubicles are larger and the heat load per square foot of space is lower. A fresh air exchange rate of 15 cph is adequate. Temperature in each

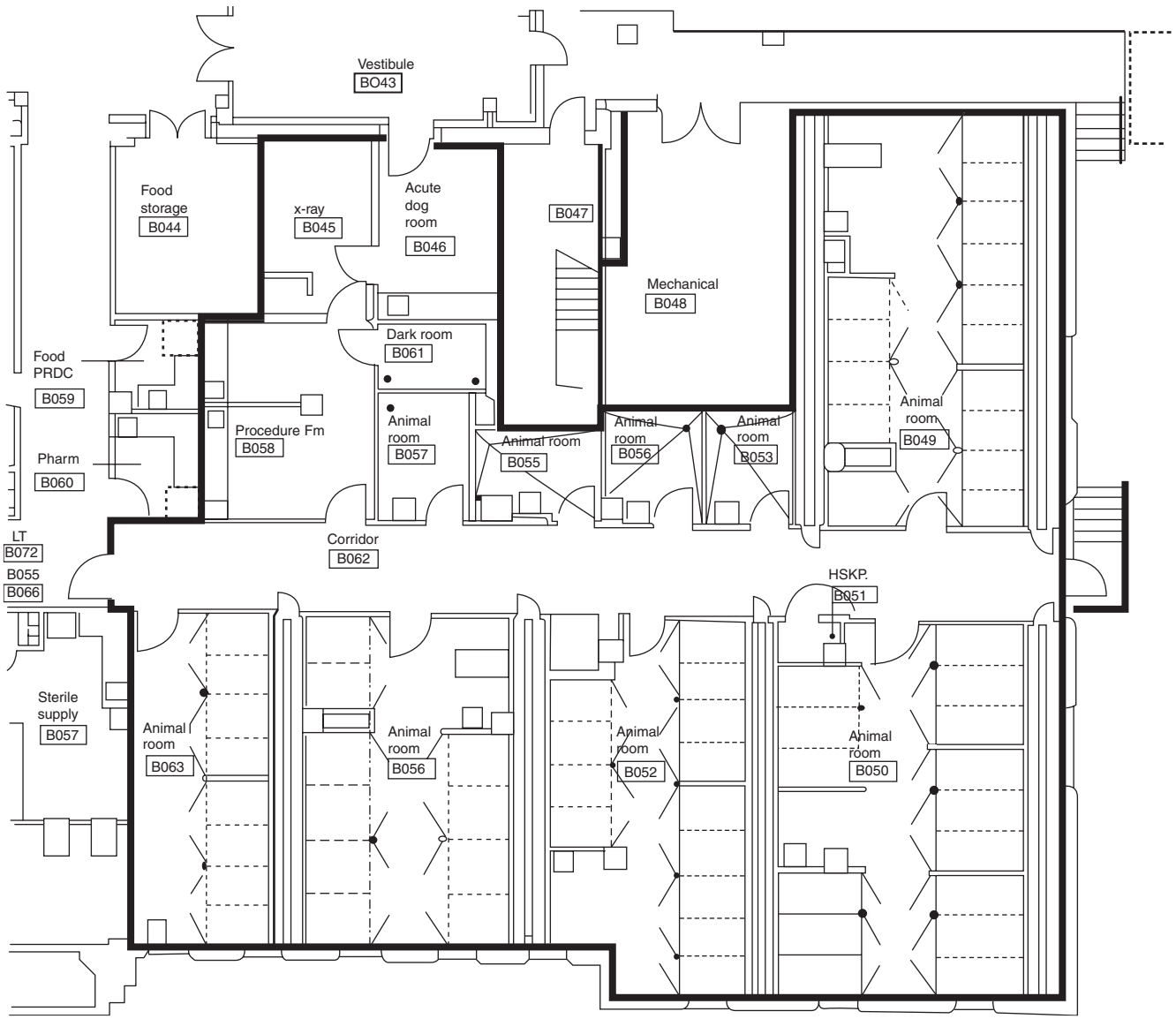

Fig. 15-13 Plan of the large animal housing suite (outlined with dark lines) of a research animal facility that includes five animal rooms with large animal cubicles and the adjacent 30″-wide service areas with drain troughs. The suite also contains four relatively small animal rooms, two animal procedure rooms, and a radiology room. A surgery suite is located just outside the large animal suite.

cubicle room can be controlled with a single terminal reheat controlled from the temperature in a common exhaust duct or the aisle between cubicles. In the cubicles illustrated in Figure 15-12, temperature cannot be controlled off exhaust air temperature because the exhaust air from two different rooms is mixed in some cases.

With both room configurations, the aisle is automatically balanced positive to the cubicles but the relative pressure at the room door must be balanced with the room negative to the corridor. Balancing ventilation exhaust with the Figure 15-12 configuration is somewhat problematic because every room is exhausted from two exhaust plenums and some exhaust plenums receive air from two different rooms; however, the only critical balancing issue is to maintain all large animal cubicle rooms and the connecting service areas negative to the corridor.

b. Lighting Requirements

Water-resistant fluorescent ceiling fixtures should provide 800–1100 lux (75– 00 foot-candles) of light 1 meter (39″) from the floor in the aisle and the cubicles. There should be a ceiling-mounted examination light located above the examination table in the animal procedure space.

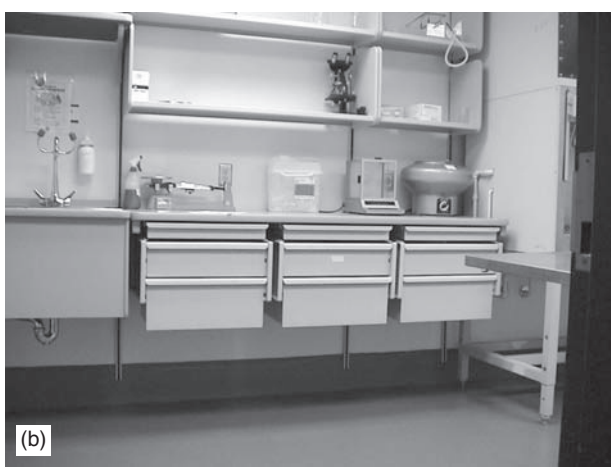

Fig. 15-14 Animal procedure area in a large animal cubicle room showing: (a) the wall-mounted sink and examination table, and the ceiling-mounted hose reel; (b) the wall-mounted counter and open design case work leaving the floor open for cleaning and reducing harborage sites for insects and vermin.

c. Power Requirements

One 120-volt duplex receptacle is required for each pen in a cubicle. It should be centered on the pens and mounted on the back wall or in the ceiling, along the side wall, 8' from the floor. In addition, a 120-volt duplex receptacle should be provided on the wall above the workstation and in the ceiling near the ceiling-mounted examination light.

Fig. 15-15 View of a 30″-wide service area for large animal cubicle rooms on both sides showing the drain trough running the length of the room and the stainless steel flashing attached to the walls that helps to direct water and waste from the adjacent pens on both sides into the trough. Also shown are the hose reel, the vertical splash panel suspended in the center of and running the length of the trough to prevent water from splashing across the trough into the next room, and the lever-controlled ball valve on the left that controls the water running down the drain trough and in the flush drain at the other end of the trough.

d. Communication Requirements

Data ports are required above the counter in the animal procedure area, and some may be required in the animal cubicles.

e. Plumbing Requirements

The following should be provided: a wall-mounted sink in the animal procedure area; one large animal drinking valve mounted on the back wall of each pen; and ceiling- or high wall-mounted hose reels in the aisle of the cubicle room and at the top of the drain trough in the service room (Figure 15-14). It is recommended that hot water be supplied to the hose reels from an independent recalculating hot water system controlled at a temperature of 110°F and a pressure of 100–120 psi. In addition, appropriate plumbing should be provided to simultaneously flush the drain trough, starting from its high end, and the trap in the 6’drain at the low end of the drain trough.

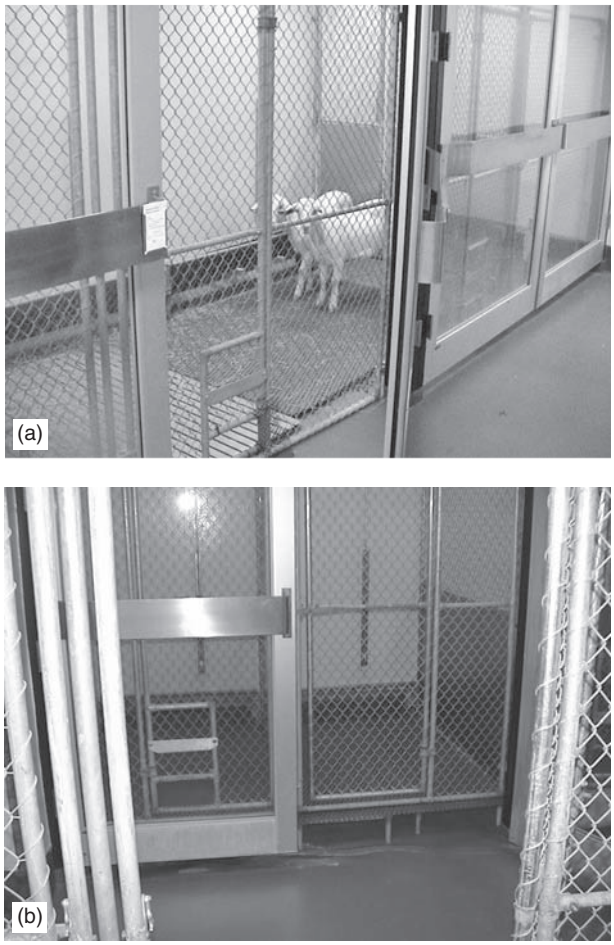

Fig. 15-16 Cubicles with fixed raised floors: (a) two adjacent large animal cubicle pens with different types of raised floors, fiberglass T-bar slats and vinyl-coated expanded metal; (b) raised vinyl-coated expanded metal floor showing a stainless-steel leg of the stainless-steel frame that supports the raised floor.

V. PREFABRICATED ANIMAL CUBICLES

"Prefabricated" generally refers to cubicle systems that are fabricated in a controlled manufacturing environment under strict quality-control practices and assembled installed on site. These systems incorporate most of the considerations listed in previous sections, thus reducing or limiting the scope of architectural and engineering work required on the project, since they are delivered to the construction or renovation site in kits that are then assembled by trained factory personnel.

A prefabricated cubicle system packages all the walls, ceilings, doors, air supply and exhaust control, filtration, lights, monitoring and communication systems needed for a complete cubicle. At the most basic level, the facility only needs to provide a 110-V/20-A power supply for each cubicle. In more sophisticated arrangements, the facility may also provide hard connections for exhaust and/or supply air. Also, data drops

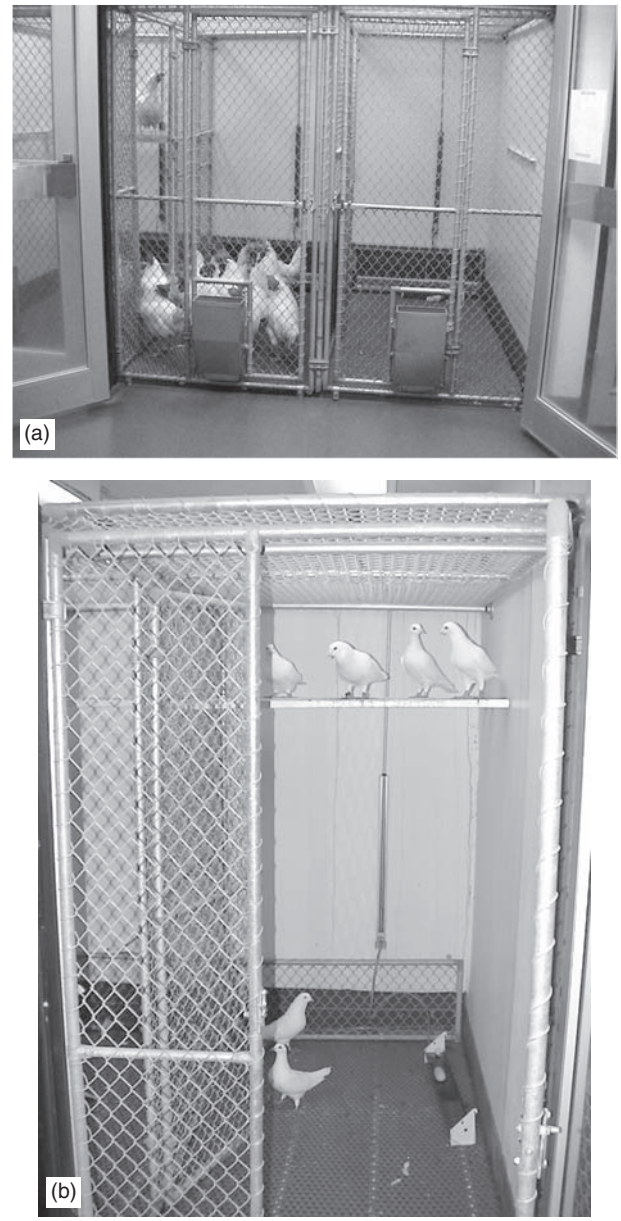

Fig. 15-17 Large animal cubicles housing birds, showing that they are useful for more than housing large laboratory animals.

may be provided for connectivity to building automation system (BAS) or office PC Ethernet networks.

Only a small number of vendors provide prefabricated cubicles, and most of these offer standard-sized systems at reasonable cost. Some are able to customize their standard cubicle systems depending on the specific goals and needs of the construction project. It is best to engage these suppliers early in the design phase of the project. A sophisticated cubicle-vendor will be able to coordinate with project architects and engineers to deliver the correct cubicle systems to meet the project requirements, and should be able to provide the architect with simple but accurate layout drawings that may be

included in building construction documents (Figures 15-19 and 15-20 provide examples). To accelerate the process, the architect should transmit room and/or building drawings to the cubicle vendor in a suitable CAD-system format. The vendor will then return room prints with their cubicle systems in place, and will identify any dimensional issues and/or interference issues. Addressing interference issues during construction documents will significantly simplify the installation process and help avoid costly last-minute change orders.

Prefabricated systems can be designed, delivered and installed to meet the needs for both small and large animal containment and isolation (as defined above). Recent trends in small animal systems include the tight integration of ventilated cage-rack systems within the cubicle space. Typically, the blower motors for the selected ventilated cage rack are mounted in the cubicle's interstitial space. The cubicle manufacture will provide special IVC blower mounts and ceiling couplings. This "containment-within-containment" solution also provides a degree of noise and vibration reduction, as the IVC blowers are now disconnected and separated from the animal holding rack. Working together, the cubicle's air system manages the macro-environment around the IVC rack, while the IVC's blowers manage the micro-environments within each animal space. Sufficiently sophisticated suppliers of cubicles and IVC racks can work together to provide an integrated package, and the cubicle's monitor and display screen can be set up to provide additional details about the IVC rack's health and status. This allows the users more easily to monitor IVC rack status without having to open or enter the cubicle space, thus avoiding unnecessary risk of contamination or disturbance of the animals.

"Double-sided" cubicles are not new, but the understanding of how this arrangement contributes to a "leaner" facility *is* new. Double-sided cubicles (Figure 15-21) allow animal husbandry and research activities to be separated, thus reducing interference between the two functions, and enable a better work flow. Animal husbandry tasks are allowed to occur in parallel with research activities. Electronic interlocks allow users to automate door/cubicle opening operating procedures, thereby minimizing the risk of cross-contamination by having more than one door open at a time.

A long-term benefit of prefabricated cubicles is that they are relatively easy to remove and relocate if future research doesn't require individual cubicle spaces. Table 15-1 provides some quantification of this long-term cost consideration.

Fig. 15-18 A row of large animal cubicles with hinged doors. Dogs are housed in the end cubicles.

A. Architectural Features

1. *Construction Materials and Finishes*

In the past, "modular" cubicles were principally constructed of stainless steel or aluminum (Figure 15-22). However, over the past 5 years composite materials have been introduced that improve the appearance and performance while reducing the overall cost of the systems. Principally, the walls and ceilings are now constructed of a structural insulated paneling system that includes a bonded fiberglass-reinforced plastic (FRP) on the outer surface. This provides a clean, bright-white surface within the cubicle space (Figure 15-23). In addition, these systems include an insulated and sound-dampening core which

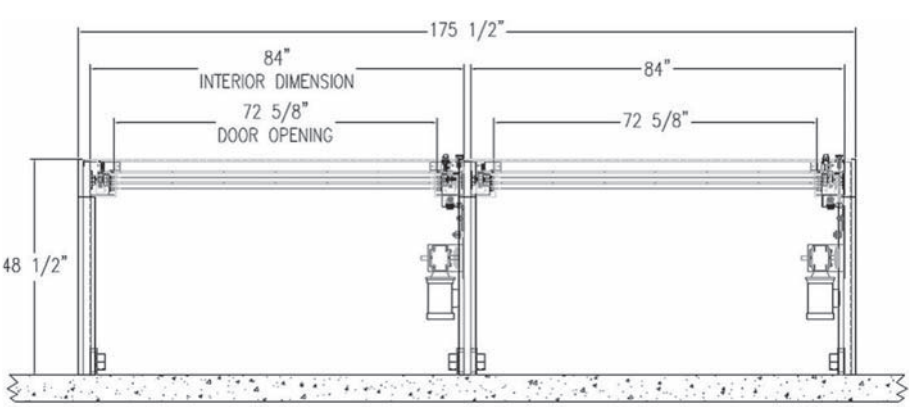

Fig. 15-19 A typical engineering layout drawing for prefabricated cubicles. Drawings like these may be integrated with architectural drawings for specific site or facility.

gives higher sound transmission coefficients (STC) than the traditional block construction of built-in cubicles and metal walls in older-style modular systems. These panels are also significantly thinner than typical block construction, which can create a significant savings in usable facility floor space (see Table 15-2). Door-jambs, trim, fasteners and other features of the cubicles will typically be fabricated from Type 304 stainless steels. Other non-corrosive materials may also be used.

Prefabricated cubicles may include a variety of door systems. Simple swinging doors may be provided, up to and including sophisticated, automated vertical sliding doors. If desired, hinged doors can be architecturally similar to other doors being used within the facility. In any case, the door systems will be consistent with the structure and materials described in previous sections.

Red-tinted glazing that blocks out light in the visible range for rodents but allows enough light transmission in the red range to provide visibility for humans is an option on cubicle doors ("Rose-Chocolate 3″ from Solar Graphics and "Vivarium Red" from Aegis Applied Films; see Chapter 33 in this book for more details. This allows normal white task-lighting to be used in the aisle outside the cubicle space, without transmission into the cubicle space and thereby disturbing nocturnal activities of rodents that may be housed inside the cubicle. It is best to have the film applied during the fabrication of the cubicle doors, but it can be completed after the cubicles are already installed. The application of the red tint is similar to that of car-window tinting, and should be applied professionally to avoid any irregularities or air bubbling. These films can be applied to either glass or polycarbonate doors, but the

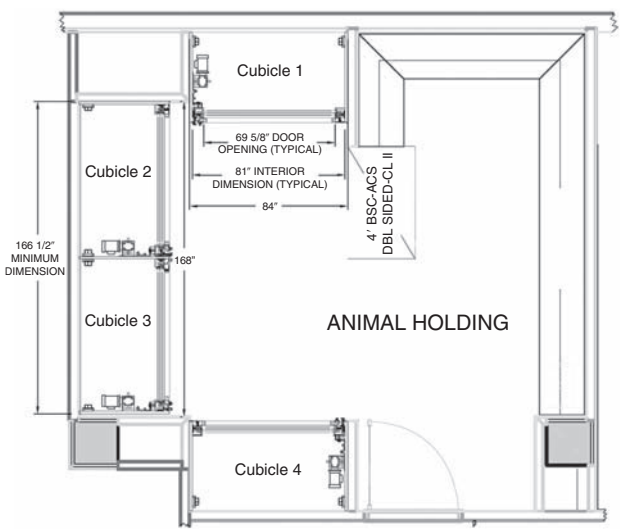

Fig. 15-20 Prefabricated cubicles shown in an example animal holding and procedure room. In this setting, four individual and separate research projects can be protected while sharing laboratory space and study equipment.

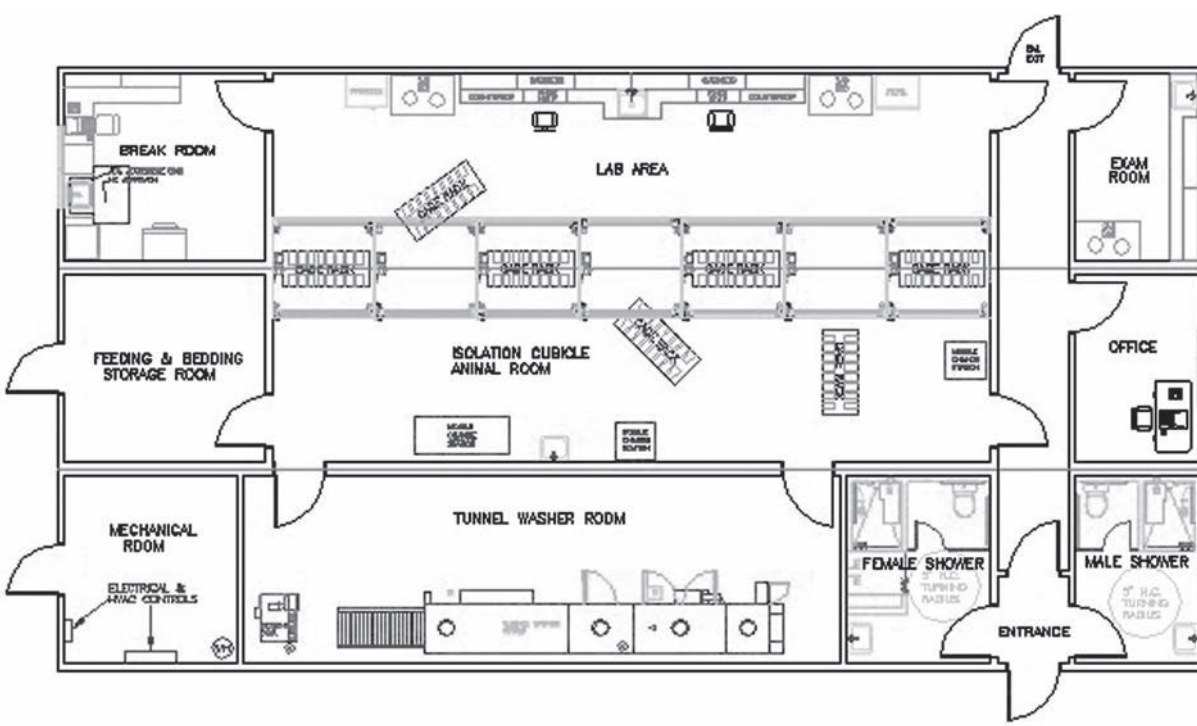

Fig. 15-21 Prefabricated double-sided cubicles. The center aisle allows for animal husbandry activities to occur without interruption of the research activities that occur in the outer aisle areas. Animals may be accessed from either side of the cubicle space. Electromechanical interlocks reduce cross-contamination risk by only allowing one door to be open at a time.

TABLE 15-1
LONG-TERM COST CONSIDERATIONS FOR CUBICLE WALL CONSTRUCTION TYPES

Primary construction methods	CMU block	Metal partitions	SIP partitions
Demolition for room renovation			
Labor costs	$1,600	$75	$70
Refinish/repair epoxy floor (3.3 sq. ft)	$280	$75	$75
Refinish/repair facility wall	$135	$40	$40
Material disposal (tipping fees ~$100/ton)	$10	n/a (recycle)	n/a (reuse)
Time required	1 week	<1 day	<1 day

Fig. 15-22 Prefabricated isolation cubicles are shown with stainless-steel divider walls. These cubicles include individual, local air-control packages with high supply and low return. Cubicles typically employ the facilities wall for the back side of the cubicle, as seen here.

process is slightly different. Usually, a clear base-layer is necessary before the red tint is applied to polycarbonate.

B. Engineering Features

1. *HVAC*

All of the ventilation options noted above for built-in cubicles are available with prefabricated cubicles. Listed below are ventilation options that tend to be unique to prefabricated cubicles, although not necessarily exclusively. In each case, excellent communication and coordination between the cubicle vendor and the building engineers is critical.

a. Option 1

Typically referred to as a "door-only" system, air is provided to this cubicle by the building HVAC systems. For cubicles intended to be used for containment, fresh air is provided by the facility system in the aisle outside the cubicle space. A building exhaust duct is pre-located within the cubicle space (Figure 15-24). As noted earlier, it is incumbent on the

Fig. 15-23 Prefabricated cubicles are shown with SIP (structural insulated panels) divider walls. These cubicles include individual air-control packages with high supply and variable high/low returns. Duct covers allow the user to "select" the type of return air (high or low) depending on the specific science demands. Note these cubicles are extra deep and allow more space for procedures inside the protected cubicle space.

TABLE 15-2
CUBICLE WALL CONSTRUCTION COST COMPARISONS

Primary construction methods	8″ CMU block	4″ CMU block	Steel partitions	SIP partitions
Wall dimensions				
Typical wall depth (feet)	5	5	5	5
Typical wall height (feet)	9	9	9	9
Typical wall thickness (inches)	8	4	1.5	1.5
Floor space required (ft^2)	3.33	1.67	0.625	0.625
Cost of 1 sq. ft of animal	$600	$600	$600	$600
vivarium space				
Vivarium space loss for wall	*$2,000*	*$1,000*	*$375*	*$375*
Total construction costs	$885	$885	$1,310	$410
Wall construction:	$555	$555	$2,310	$410
brick & mortar	$9/$ft^2$	$9/$ft^2$	$1,250/ wall	$350/wall
brick mason (hourly)	$30	$30	$30	$30
construction rate	1 linear ft/h	1 linear ft/h	2 <2 h/wall	2 <2 h/wall
Painting:	$165	$165	–	–
2-part epoxy paint	$165	$165	–	–
labor	$100	$100	–	–
epoxy cure time	?/	??	n/a	n/a
Coving:	$165	$165	–	–
materials	$100	$100	–	–
labor	$65	$65	–	–
cure time	24 h	24 h	–	–
Time upfront cost for wall types	$2885	$1885	$1685	$785

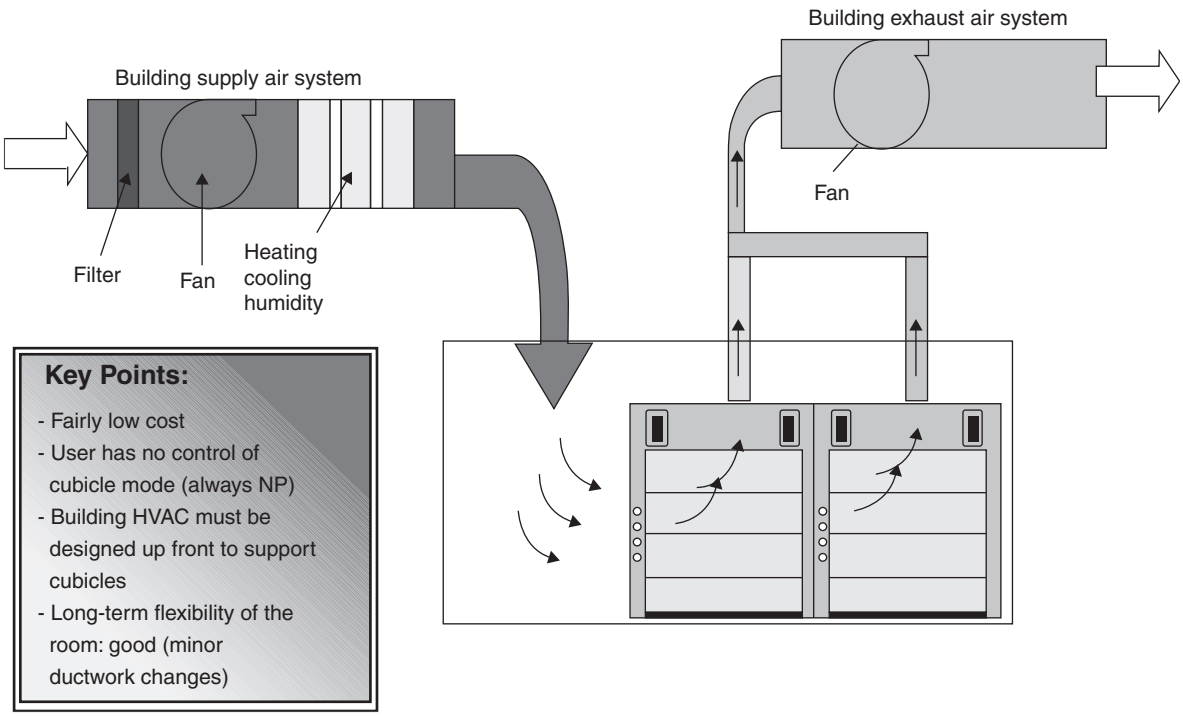

Fig. 15-24 Site-built HVAC for negative-pressure (containment) cubicles. A building exhaust duct must be located within the cubicle space. Typically, air flows from the aisle and into the cubicle through a gap (~1′) under the door.

facility HVAC system to balance the air in the cubicle room such that the aisle is maintained with a positive delta pressure with respect to the cubicle space. For cubicles intended to be used for isolation, the building HVAC must be reversed, with supply inside the cubicle and exhaust located in the aisle way (Figure 15-25). The cubicle space(s) are then maintained positive to the aisle. Generally speaking, this is not a very flexible option, as the purpose of the room (containment or isolation) will be fixed virtually forever.

b. Option 2

Arguably, the most important option of modular cubicles is a self-contained air-control system. Such cubicles are generally referred to as "full cubicles," and air is controlled within the cubicle space with the use of self-contained blower systems. These cubicles include built-in air-flow monitors and control features. End-users have the ability to select the "mode" of operation of the cubicle as either positive or negative. In simple systems, airflow is controlled with manual valves located within the cubicle's duct work. Users set the conditions by trial-and-error balancing of airflows in the cubicle. More sophisticated cubicles utilize electronic measuring devices to monitor airflows. Then programmable logic controllers (PLCs) automatically adjust supply and exhaust airflows to maintain the desired cubicle conditions. In addition to providing air control, these cubicles may also provide HEPA filtration for both supply and exhaust air circuits.

c. Option 2A

In the simplest situation, the cubicle room is designed with the building's supply and exhaust in the aisle-way. The cubicle's supply blower draws fresh air from the aisle, filters it and then injects it into the cubicle space (Figure 15-26). The location of the supply diffuser may differ by vendor, but typically is located in the ceiling of the prefabricated cubicle. The cubicle's exhaust blower extracts air from the cubicle space, filters it and then dumps it back in the aisle. The principle issue with this method is that 100 percent fresh air will not be provided to the interior of the cubicle.

d. Option 2B

This is similar to Option 2A; however, the output of the exhaust blower is connected directly to the building's exhaust network. Practical experience has shown that a thimble connection works best, allowing the cubicle to dump exhaust air, while the thimble allows the room to maintain balance whether the cubicle is operating or not. This arrangement is generally the most typical arrangement, as it allows 100 percent fresh air to be provided to the cubicle space.

e. Option 2C

The third variation requires both the supply *and* the exhaust blowers of the cubicles to be connected to the building's

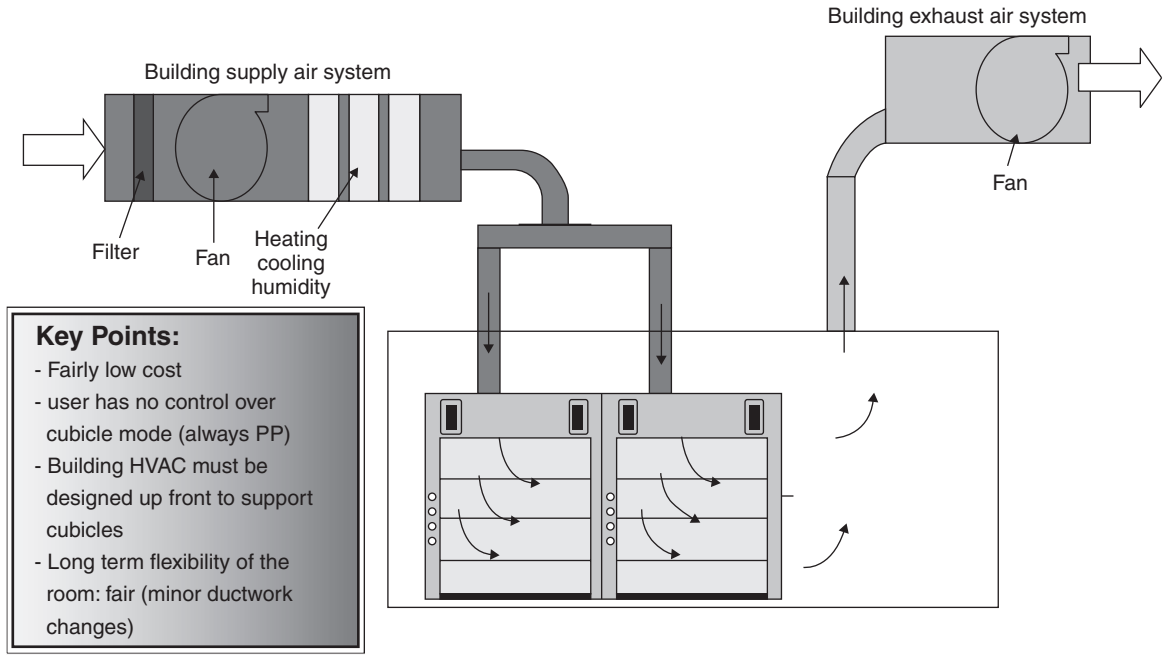

Fig. 15-25 Site-built HVAC for positive-pressure (isolation) cubicles. A building supply duct must be located within the cubicle space. Typically, air flows from the inside of the cubicle through the bottom door-gap to the aisle.

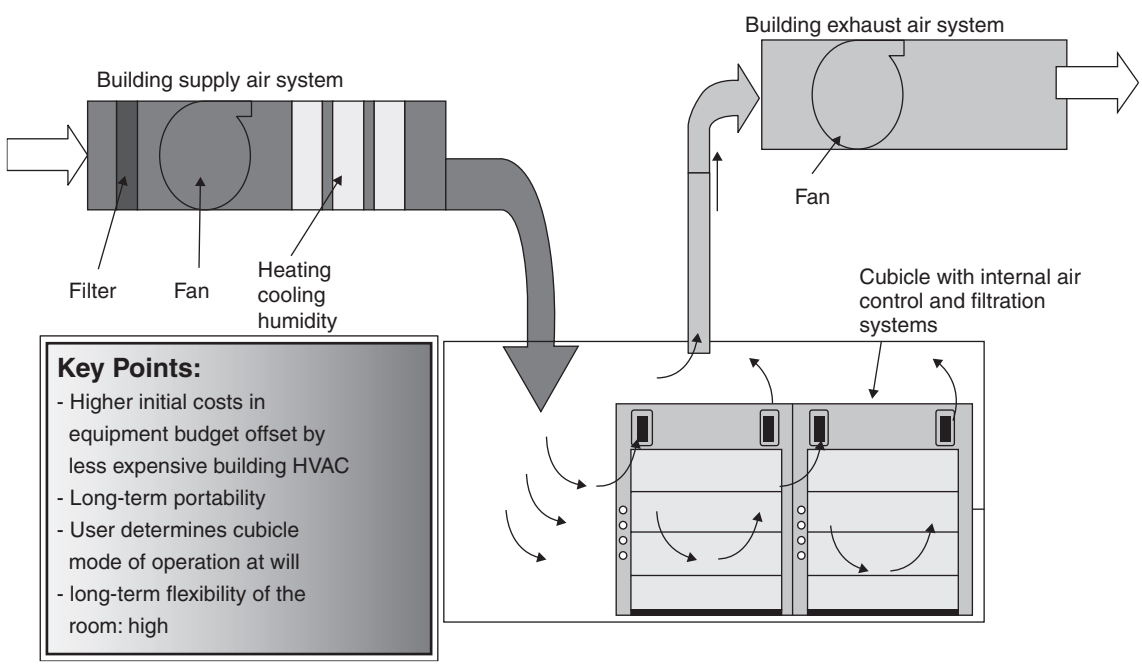

Fig. 15-26 Prefabricated cubicles with built-in variable-pressure air control systems. In simple systems, users adjust airflow manually using a set of air control valves. In sophisticates systems, airflow in the cubicle is controlled automatically via closed-loop programmable control systems.

HVAC network. As noted above, thimble connections for both connections are preferred. This allows the building to continue to supply and exhaust the room, regardless of the state of the cubicle – i.e., if the cubicle is powered down for some reason, the room will still be ventilated properly. This is the most challenging option, and requires the most coordination between the cubicle vendor and the building's mechanical and HVAC engineers.

2. *Lighting*

Lighting may be provided in the variety of methods described earlier, with either ceiling-mounted lighting or vertically-mounted fixtures at the corners of the cubicle space. In prefabricated cubicles, an automatic timer is provided which allows the user to program diurnal (on/off) cycles inside the cubicle space. Digital ballasts may be selected that allow the intensity of the lights to be set at a lower lever (30 foot-candles) for normal "daylight" periods. A temporary override (or secondary timer) may be provided that allows the lights to be brought to full output (80 foot-candles) for husbandry or research tasks. The secondary timers will automatically drop the light intensity back to the lower setting after a short period of time.

3. *Power*

120-V duplex outlets are a common option inside prefabricated cubicles. There must be consultation with the supplier to verify that this option will be provided. Depending on the power demand for the equipment to be used inside the cubicles, the facility may need to provide a second dedicated circuit for this outlet.

4. *Communication*

Data ports are also a valid option to request with prefabricated cubicles. More importantly, automated cubicles can provide data to building automation systems (BAS) and/or office PC Ethernet networks. This enables remote monitoring and control of the cubicle spaces from virtually any location. Some vendors may also provide specialized remote management software that can provide data logging and alert messages through cellular paging systems or email.

5. *Temperature and Humidity Control*

This is an expensive option, but independent and self-contained environmental control is available in some prefabricated cubicles. Two options exist, and are summarized below.

a. Option 1

Basic temperature control is provided via re-heat coils within the supply ductwork. There must be consultation with the cubicle vendor to determine the building supply air requirements. Typically, the building must provide air at 60°F to the cubicle. The cubicle's reheat system will then bring the cubicle space to the desired temperature.

b. Option 2

Temperature and humidity control is provided via re-heat coils and humidification systems. Again, close coordination between the cubicle vendor and facility engineering will be required. Typically, the building must provide air at 55°F, with <50 percent relative humidity. In addition to higher electrical power demands, the humidification system will require a constant source of water.

6. *Customizations*

Prefabricated cubicles can easily be customized to meet specific site and/or research needs. As noted above, custom cubicles can be built in a controlled factory environment where tight tolerance and high quality can be maintained. The cubicles can then be delivered and easily assembled at the facility. When considering this option, the following considerations must be kept in mind:

- 3-D engineering design software should be used to fully model the proposed system. These design systems will allow inspection of dimensional clearances and operational features before committing any dollars to physical materials.
- Implementing a prototype and/or executing a factory acceptance test (FAT) of the first unit will allow for a hands-on, functional inspection of the selected design.
- Finally, it is worth considering investing in third-party commissioning upon completion of the installation of the units in the facility.

Figure 15-27 provides an example of a customized cubicle system designed for high dust containment environments. This is an example of how two cubicles with self-contained air supply systems are combined to form an anteroom and procedure room. Under normal conditions, the procedure room runs negative to both the anteroom and the aisle-way. Users enter the procedure room through the anteroom via a set of hospital-quality swing doors. A larger entry door to the procedure room is used infrequently for installation of large equipment for animal housing or study.

7. *Security*

Physical security of individual cubicles may be an important feature in certain biosafety facilities. It also may be valuable where independent research projects are co-located in the same cubicle room (but separate cubicle spaces). Cubicles controlled by a programmable logic controller (PLC) may include physical access control to each cubicle via an electronic pass key. In addition, the PLCs of the cubicles in each room may be interconnected and interlocked. This feature allows the cubicles' electronic systems to further mitigate potential cross-contamination. By interlocking the cubicles, only one cubicle door may be opened at a time in the same room.

VI. CONCLUSION

Animal isolation cubicles have been used extensively since the 1960s and have proven to provide effective isolation, controlling

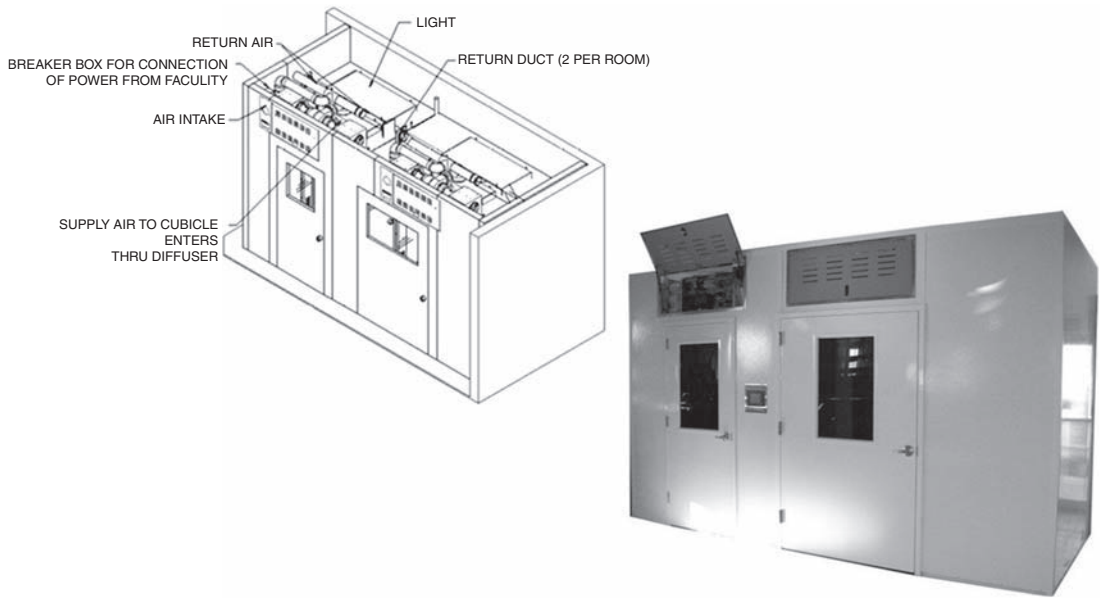

Fig. 15-27 Prefabricated high-containment cubicles with integrated anteroom connected directly to procedure room. Gasketed hospital doors with an automatic drop threshold provide a tight seal under negative pressure. Automated controls maintain procedure room negative to anteroom, and entire system negative to the aisle.

cross-contamination between cubicles in the same room. They continue to be useful when separation or isolation of small groups of small or large laboratory animals is required. Cubicles are a viable renovation option when an animal facility has sufficient animal housing space but insufficient spaces to meet the need for separating and or isolating animals for myriad reasons. They are especially useful for quarantine of animals of known or unknown health status, and for containment facilities. The concept is simple, yet the design details are relatively complex. The many architectural and engineering features to choose from require careful consideration in order to satisfy the requirements of each facility. As is often the case, there is not one best way to design animal isolation cubicles.

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Chapter 16

Modular Buildings

Clifford R. Roberts and William E. Britz, Jr.

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I. INTRODUCTION

Modular buildings have been used in support of animal research programs for many years. Early modular buildings were constructed primarily as an offshoot of the mobile-home industry, or by the modification of large truck trailers. The animal-care facilities prepared for the support of NASA's Project Mercury Animal Flights (*circa* 1950–1962) were modified semi-truck trailers. The trailers were totally lined with stainless-steel panels and the floors were finished with seamless vinyl floor covering. Stainless-steel cabinetry and other fixed equipment, such as surgical tables, surgical lights, sinks, etc., were installed in the trailers just as would have been done in a conventional animal facility. Four trailers were configured as: treatment/surgical rooms, animal holding rooms, and animal training laboratories. Figures 16-1 and 16-2 show the exterior of the trailers and a typical animal holding room, respectively.

More recently, a number of companies have specialized in manufacturing modular buildings for a variety of purposes; among these have been companies specializing in animal-care and -use facilities, diagnostic laboratories, and even high containment laboratories. In doing so, they have developed several specific construction methodologies. These can be grouped into three general categories: structures with fiberglass shells (exterior and interior walls with a sandwiched foam core), wooden structures, and steel structures. All of these will be addressed in more detail later. The complexity of modular facilities for these uses has also expanded from a single unit to multiple units – in some cases even multiple storeys.

Fig. 16-1 NASA Project Mercury animal support trailers in assembly.

Fig. 16-2 Animal holding room in a NASA trailer.

It is interesting to note that some of the most complicated and sophisticated modular buildings have been developed supporting the pharmaceutical industry. These modular buildings are highly complex, primarily constructed of steel frames, consisting of many modules, assembled on several levels (storeys), and filled with highly technical equipment and utilities. The modules are manufactured in a large factory, fully assembled and tested for proper operation of all functions, then disassembled, transported to the customer's site, reassembled and commissioned. This process has proven to give the pharmaceutical customer the opportunity to expand rapidly and provide production facilities to meet tight manufacturing schedules and extremely rigorous FDA requirements for bringing new drugs to the market quickly.

Similarly, more and more modular building projects for animal care and use have been initiated to quickly provide additional space for recruiting new investigators, and as "swing space" for holding valuable animal colonies during construction and/or renovation of older facilities.

Fig. 16-3 Modular rodent housing buildings installed in a warehouse.

II. THE "GOING MODULAR" DECISION

The decision to use modular construction for a new facility is dependent upon many factors. One of the first decisions, and in some cases the most difficult, has to do with "esthetics." In most cases, the campuses of universities, pharmaceutical companies and planned research parks have strict building codes in place to maintain a desired image. Clearly, with the appropriate architectural and engineering input, modular buildings can be designed to fit into most campus images very well. A wide variety of exterior finishes and architectural fixtures are available which can be applied to mimic existing construction in the area. In addition, the modular buildings can be located inside existing structures such as warehouses, or placed on top of existing buildings and shielded from view with skirting and other barriers. For smaller biotech organizations, modular buildings have been installed successfully in the warehouse portion of "office/warehouse" facilities and are totally hidden from the surrounding neighborhood. In these cases, the modulars are not given exterior finishes or roofing, which can represent a considerable cost saving. Figure 16-3 shows five modular units installed in a warehouse for housing rodents, while Figure 16-4 shows the interior of one of the buildings with ventilated rodent cage racks installed.

A good example of what can be done architecturally in a modular building design is shown in Figure 16-5. This is the first "anchor" building in a new off-campus research park at a large Southern university. The building was designed as a BSL-2/BSL-3 animal research facility supporting a world-class research program in feline immunodeficiency diseases. The building includes three modules: two each 16′ wide × 92′ long, and one 32′ × 16′ wide placed across the ends of the two long modules. Figures 16-5 and 16-6 show some of the interior areas and finishes of the building, while Figure 16-7 illustrates a support area.

Modular facilities constructed for laboratory applications can be highly technical, and can include the most sophisticated equipment. The photograph of a state diagnostic laboratory shown in

Fig. 16-4 Interior of the rodent housing buildings with ventilated cage racks installed.

Fig. 16-5 A modular BSL-2/BSL-3 animal research facility.

Figure 16-8 demonstrates banks of HEPA filters and specialized exhaust stacks on the roof. It also shows the duplicated heating, ventilation and air conditioning (HVAC) units and the back-up diesel-powered generator that is provided for emergencies.

Fig. 16-6 Interior corridor with small animal holding rooms on each side.

Fig. 16-7 Animal-care entry and support area.

Fig. 16-8 A highly specialized state diagnostic laboratory built with modular construction.

III. MODULAR BUILDING CONSTRUCTION

Modular facilities, whether a single module or multiple modules which are assembled together to form a cohesive building, are generally constructed in a factory where changing seasons and inclement weather do not affect the construction schedule. These are generally large open-bay manufacturing facilities in which several modules can be in various stages of production as they are moved along an assembly line.

The manufacturing process starts at one end of the assembly line with the assembly of a base unit which will support the rest of the construction. Bases can be any of several designs, depending upon the individual manufacturer, and can vary from welded steel frames with steel floor joists and a corrugated sheet metal pan into which a concrete floor is poured, to wooden frames constructed of a double rim joist and floor joists of 2-inch structural lumber screwed or nailed together with plywood decking of 1 1/8th-inch tongue-and-groove marine plywood to form the floor of the facility.

Both of these base designs can be finished with a variety of floor finishes or floor coverings in the same way the floors of a stick-built facility would be finished, including troweled epoxy floors and coving. When a wooden base and floor are used, the entire deck is generally sealed with an epoxy sealer before the floor covering and wall structures are added.

The walls of modular buildings may be constructed using steel studs and various interior finishes, including plywood, gypsum wall board, green board, or cement board for extra waterproofing, or various specialized wall-board systems providing the wall structure and the surface finish in a composite panel. Engineered wall panels featuring steel tubes for strength and expanded polystyrene (EPS) foam for insulation may also be used. The specific designs are proprietary to individual manufacturers, and provide a variety of specifications for load support, insulation "R" factors, and interior and exterior finishes. Wooden wall construction may be accomplished using standard 2×4 or 2×6 stud framing and the same interior and exterior wall finishes as stated above. Another popular wall construction method uses structural insulated panels (SIP), which are high-performance building panels used in floors, walls, and roofs for modular and conventional buildings. The panels are typically made by sandwiching a core of rigid foam insulation between two structural skins of oriented strand board (OSB). Other skin material, such as plywood, can be used for specific purposes. SIPs are manufactured under factory controlled conditions, and can be custom designed for specific purposes. The result is a building system that is extremely strong, energy efficient and cost-effective. Constructing walls with SIPs is extremely fast and saves labor.

Interior walls in modular buildings are generally not supporting walls, and are usually constructed with steel or wooden studs. In some cases, temporary walls may be installed for support during shipping and removed when the modules are connected at the building site.

Interior wall surfaces of modular buildings can be finished with fiberglass-reinforced plastic (FRP) paneling, which provides a smooth and durable surface. FRP panel sheets can easily be bonded to the interior skin of the SIPs. Vinyl batten strips are applied at the panel joints, and sealed to provide a waterproof interior surface. The batten strips also cover the panel fasteners, providing a clean and uniform appearance.

Manufactured trusses are generally used for the ceiling and roof structures on modular buildings. These may be welded steel or wooden trusses. The design of the trusses is specialized to allow the installation of HVAC ductwork and other utilities such as water, gas, and electrical conduits when necessary. The trusses are also formed appropriately to provide either gabled or a flat roof design. In the case of multiple-storey modular buildings, the base, wall structures and roof trusses are engineered to support the weight of the additional modules stacked on top.

The exterior finish on modular buildings can be any of a number of available materials, depending upon the desired finished look. The materials can vary from baked-on enamel steel siding, to stucco, brick or stone veneers, or epoxy-type paneling such as Trespa®.

A variety of roofing materials and roof lines also can be applied to meet the desired architectural appearance. The roof can be constructed as a flat roof or a gabled roof. Gabled roofs are usually used for buildings composed of one or two modules, and may be finished with any of several roofing materials, including composition shingles, tiles, or steel roofing panels. Flat roofs are usually finished with a built-up foam structure to provide drainage, and covered with a seamless "rubberized" EPDM (ethylene propylene diene monomer rubber) membrane roof covering which is securely fastened around the edges.

As indicated earlier, modules that are designed for installation inside larger buildings do not require the exterior finishes or roofing necessary for weather protection. In fact, many utilities and other building support equipment may be installed on top, alongside the building or attached to the exterior, as needed. Installation inside a larger building can also provide added security for the animal-care operation, and environmental functions of the main building may be used to control the environment within the module(s) if those systems have the necessary capacity. Also, some support of the functions for animal care (such as cage-washing and extra caging and feed storage) may be located outside the modules within the open area of the larger building.

Modules can vary in size, but in the end the size is restricted by shipping limitations. Each module has to be individually shipped by truck on large lowboy semi-trailers or special "heavy hauler" multiple-axel transports from the manufacturer to the building site. Modules are typically up to 70 feet long by 15 feet wide by 15 feet high; although modules as wide as 16 feet can be shipped in some situations and modules

as long as 94 feet have been transported long distances across multiple states on the interstate highway system. The various states have individual restrictions for weight, length, width and height for transporting the modules; these must be taken into account when planning a modular building project. Special permits are required which may prescribe the hours that travel can occur and which routes may be used. Pilot cars and escorts will generally be required for moving the modules on public highways. Some smaller modular buildings consisting of one or a few smaller modules may be transported on special steel frames (chassis) and axels similar to those used for mobile homes, and pulled with a special short-wheelbase truck which is highly maneuverable. In some situations, the smaller modules transported in this manner may be backed over the prepared foundation and lowered onto it without the use of expensive cranes. One or more large cranes are generally necessary for unloading and setting the larger modules on the prepared foundations.

IV. ENVIRONMENTAL FACTORS

Modular buildings, as with any building project, must be designed to meet the requirements for the environmental and climatic conditions that exist at the installation site. Factors such as temperature and humidity ranges, prevailing winds, possible snow loading on roofs, flooding conditions and other extreme weather/locality episodes (such as hurricanes and/or earthquakes) must be considered. Because of the fact that modular structures must be structurally sound in order to survive transportation from the factory to the installation site, and to withstand lifting and craning operations, they are naturally more resistant to damage from earthquakes and hurricanes.

The building insulation and HVAC systems are designed specifically for the climatic conditions that will be encountered at the installation site. In some instances, back-up power generators and duplicated HVAC systems have been included to ensure there will be no failure and the possible loss of valuable research animals and equipment.

V. MODULAR BUILDINGS AS "TURN-KEY" BUILDING PROJECTS

Probably the greatest benefit of using modular buildings is the ability to have them delivered as "turn-key" projects in which the supplier designs, engineers, builds, transports, installs, tests every function, and commissions the building prior to handing it over to the customer. Essentially, the building is ready to be occupied and function, "at the turn of a key." As the modular building progresses through the factory, every piece of equipment required in the building is installed, tested and certified, which prevents incompatibility problems in the final product. This process, coupled with the construction of the modules in a factory where weather has no effect on the construction schedule, allows a much greater probability of the modular building being delivered on time and without change orders.

Figures 16-9 and 16-10 provide examples of a typical laboratory and a fully equipped necropsy room, respectively, that have been provided in turn-key modular building projects.

VI. LOCAL ZONING AND BUILDING CODES

Modular buildings, as with any building construction, must be in compliance with the local zoning and building codes. The modular buildings must comply with the codes in the area of the installation site, not the factory. This can present issues

Fig. 16-9 A typical laboratory with installed cabinetry, sink, and a biological safety cabinet.

Fig. 16-10 A fully equipped necropsy room in a modular building.

with having the required inspections conducted by authorized building inspectors from the site location. Local building inspectors may have to be flown to the manufacturer's plant to view the construction before it is closed up in the modules. It should be decided ahead of time whether this cost will be borne by the owner or the manufacturer. In some cases, states have requirements for modular building manufacturers to be "certified" by that state in order to produce modular buildings intended for delivery in that state.

VII. COST CONSIDERATIONS

The cost of a modular facility vs a "stick-built" facility (one constructed on site from the ground up) presents many specific costs in both instances that must be considered and weighed against each other. Architectural and engineering costs associated with any building project can be considerable. With a stick-built building project, these are almost always one-time costs specific to the project. With modular building projects, the manufacturer can frequently re-use designs for standard building components and modules, resulting in lower fundamental engineering and design costs. Additional savings can be realized in the modular building process by conducting parallel paths for different systems and simultaneous work on separate modules in different stages of completion. In addition to the cost savings, these processes can also result in significant time savings for the completion of a modular facility. As a matter of practice, the preparation of the site and the construction of the foundation and installation of utilities on the site can occur during the construction of the modules in the factory, saving considerable time in the overall project.

Other costs which must be considered include the cost of transporting the modulars from the factory to the building site, and the variability of labor costs at the factory and at the building site. In both situations, possible labor union conflicts and prevailing wage structures must be considered.

VIII. SUMMARY – MODULAR BUILDINGS, PROS AND CONS

In summary, the following pros and cons should be evaluated when considering modular buildings as a solution to providing new animal-care and support facilities.

A. Pros

- *Shortened construction time.* Site preparation concurrent with building construction and the construction of the modular buildings in a factory precludes weather delays, which can shorten the construction time significantly. This factor alone can be a "make or break" consideration for providing new space for the critical recruitment of research projects and personnel.
- *Reduced possibility of cost escalation.* Most modular building projects are fixed-price contracts agreed upon before the start of the project. Cost escalations due to material price increases or labor costs increases during the life of the project are reduced as a result of the shortened time required for completion.
- *Improved quality of the final product.* Factory-style quality control procedures and highly skilled, committed, long-term employees contribute to higher quality work.
- *The ability to relocate.* In the event the project needs change, and with proper initial planning for the modular building(s), they may be sold and/or relocated to conserve capital assets.
- *Increased safety.* The implementation of factory safety procedures and less on-site effort contributes to an overall safer work situation.

B. Cons

- *Costs may be greater than stick-built.* While the costs of construction in a factory are usually less, transport costs can be significant.
- *Changes in the design during manufacturing can be difficult and expensive to accommodate.* Modular design must be precise, and does not allow for changes.
- *The general impression that modulars will not complement existing buildings.* The ability to provide architecturally pleasing and conforming buildings must be "sold."
- *Transportation restrictions may cause design limitations.* Individual state's transportation and roadway regulations may impact the size and weight of the modules.
- *Code compliance and the inspection process may be more complex than with a stick-built facility.* Inspections for code compliance must be closely coordinated with building inspectors from the installation site.
- *There is the potential for creating labor disputes with local unions.* Factory installation crews are usually non-union, and each of the individuals on the crew may cover several trades.

Chapter 17

Common Facility Design Errors and Problems

Noel D.M. Lehner and Jack R. Hessler

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I. INTRODUCTION

There are multiple solutions to address the myriad of factors that influence the design and construction of research animal facilities. Solutions are often compromises between what is desired and deemed appropriate, and what is dictated by time, money and other resources. Even with limited constraints, however, the perfect solution for design and construction may not be achieved. What seemed good in the planning phase may not always work out well in operation of the facility. In the end, results may leave something to be desired, and some things would be done differently were this possible. This following discourse is the compilation of common or significant problems encountered by Diplomates of the American College of Laboratory Animal Medicine and their associates that resulted in less than optimal maintenance and operations.

II. ARCHITECTURAL ISSUES

A. Planning, Design and Construction Team Issues

1. Architectural/engineering firms not experienced with animal facilities.

2. Contractor not experienced with animal facilities.
3. Independent commissioning agent not used or not involved early in design and construction.
4. Not having physical plant staff directly involved in design and construction meetings.
5. Exclusion of animal resources staff from "value engineering" considerations.
6. Failure of the animal resources staff to be fully engaged in the project from planning to commissioning.

B. General Layout Issues

1. Locker rooms not at entry to a facility that requires donning of PPE for entry.
2. Locker rooms located inconveniently or near soiled cage-wash area.
3. Air locks not provided at entry and exit to facilitate barrier operations.
4. Insufficient isolation of non-human primates. Non-human primate housing not segregated from other animal housing and a requirement for non-human primates to be transported across common hallways to procedure rooms.
5. Indirect route from animal rooms to cage-wash.
6. Indirect route from loading dock to animal facility.
7. Common elevators for transport of animals and people.
8. Quarantine area in the midst of regular housing.
9. Insufficient separation between break room and animal rooms.
10. Janitorial closets not provided in all appropriate locations (surgery suites, barrier and containment suites).
11. Separate entry air locks not provided in barrier facilities for personnel and for supplies such as animal transport boxes that may need to be chemically sanitized prior to being introduced into the barrier.
12. Design does not facilitate efficient and effect flow of traffic in the facility. Flow cycles for movement of personnel, animals, and material into, out of and within the facility not carefully planned.

C. Interior Finishes/Surfaces

1. Floors, especially in cage sanitation, fail, by either being too soft or delaminating.
2. Walls constructed with non-durable materials and inadequately protected.
3. Ceilings not adequately moisture-resistant – especially a problem in cage sanitation areas but also in large animal rooms where hoses are used for daily cage- and pen-cleaning.
4. Non-sanitizable finishes for loading dock and receiving area.
5. Lack of ceiling in mechanical spaces.
6. Ledges and crevices that are difficult to clean and sanitize.
7. Pinholes in finished concrete block; inferior block/inadequate preparation.
8. Block filler incompatible with paint, resulting in the paint peeling off in large sheets within less than a year.

D. Doors and Doorframes

1. Constructed of high-maintenance materials – e.g., painted metal doors and frames that need to be painted every 3 years in preparation for an AAALAC International site visit.
2. Inadequate size, not wide enough and/or high enough to accommodate the cage types. Animal room doors may be high enough for tall cages, but the cage-washer doors and/or other doors, including elevator doors, not high enough to permit the cages to be transported to and through the animal facility.
3. Metal view-panel doors with squared-off corners create a hazard when the doors fail to stay closed.
4. Failure to provide protective hardware.
5. Access control not provided.
6. Latches unprotected or recessed and difficult to use.
7. Failure to provide automatic doors in high-traffic areas such as corridors and the cage sanitation area.

E. Floors

1. Resin floors with too much grit, impeding sanitation; use "orange peel" texture for non-slip, cleanable surface.
2. Inconsistent quality of floor. Have one room finished and accepted before doing entire job. Require all floors to meet qualities of the accepted floor.
3. Floor cove surface very rough and difficult to clean and sanitize.
4. The top of the floor cove base is not feathered to avoid a dust collection site.
5. Expansion joints in middle of room resulting in a sanitation problem.
6. Poor workmanship in floor preparation and installation resulting in delamination and early deterioration.
7. Epoxy and floor sealers that discolor over time from exposure to light.

F. Animal Rooms

1. Designed for specific species or program with all rooms the same size. One size does not fit all, and a mixture of small, medium and large rooms is more flexible and efficient to accommodate changes.
2. Allowances not made for mop buckets, hanging mops, hose bibs, cleaning supplies and researcher supplies.
3. Inadequate number and size of animal rooms.

4. Planning unrealistically high room cage-density to meet needs. This may result in rooms that have inadequate space between rows and aisles of racks, making it very difficult for animal resources and research staffs to work in the rooms. Such conditions greatly reduce staff efficiency.
5. Animal rooms too small to accommodate a BSC or change station cabinet.

G. Animal Procedure/Laboratory Space

1. Failure to consider that many animal procedures are now done in the animal facility. This requires a much higher percentage of the total space to be dedicated to animal use than had previously been necessary. In addition, the types of animal-use space have expanded to include laboratories for creating transgenic and knockout (KO) animals, sophisticated imaging equipment and behavioral laboratories for neurological phenotyping of transgenic and KO animals.
2. Inadequate procedure space in rodent barrier facilities. Consider a small procedure/anteroom for each barrier room.
3. Failure to provide lead shielding for core imaging laboratory.
4. Inadequate storage space in the animal facility for investigator's supplies.

H. Cage Sanitation Facility

1. Lacks separation of clean and soiled sides of the cage sanitation area with pass-through cage-washers.
2. Insufficient workspace for:
   a. pre-cleaning cages
   b. setting up cages prior to use
   c. filling and storing water bottles.
3. Inadequate storage space for:
   a. clean cages
   b. sanitation chemicals.
4. Feed and bedding storage too remote from the cage sanitation facility.
5. Floors not appropriately sloped.
6. Ventilation inadequate to handle the heat load.
7. Inadequate exhaust resulting in high humidity and peeling paint.
8. Inadequate or inappropriate equipment for sanitizing cages, equipment and water bottles.
9. Inadequate logistical considerations for handling tons of clean and soiled bedding.
10. Use of ramp to load and unload the washer in lieu of having a pit to make the washer floor level with the room floor.
11. Failure of paint and/or block filler to adhere to block walls, especially in wet areas (e.g., cage sanitation) and canine/large animal rooms, is a common problem and once it starts repainting is rarely a long-term solution. Using fiberglass-reinforced panels over the block is a viable solution when the problem occurs. In new construction, ceramic tile wall covering or ceramic glazed block with epoxy grout eliminates the potential problem. In addition, for ceilings in wet areas, especially in cage sanitation areas, consider using water-impervious materials that do not require painting.
12. Unfinished ceilings in cage-wash precluding the ability to provide adequate sanitation.

I. Support Space

1. Inadequate storage space:
   a. inadequate staging/set-up space for clean cages
   b. storage space for clean cages separate from clean side of cage-wash
   c. inadequate storage for food, bedding, and other supplies.
2. Inadequate facilities for men and women's locker rooms.
3. Inadequate break rooms and administrative/training space

J. Special Requirements

1. Lack of automated environmental monitoring (temperature, humidity and light cycles) and alarm capabilities for all animal rooms.
2. Failure to provide appropriate animal-drinking-water quality, e.g., reverse osmosis water.
3. Failure to build in appropriate accommodations for installing automatic watering-post construction, even if not planned to be used at the time of facility programming.
4. Inadequate electronic security and access control into and within the facility, such as barrier, biocontainment, quarantine, primate areas, etc. as well as individual animal rooms.
5. Use of conventional keys. Keys are impossible to track and control.

K. Corridors

1. No provisions to store cleaning equipment, including mobile floor scrubbers.
2. No provisions for PPE stations and disposal receptacles for disposable PPE.
3. Grossly inefficient layout created by combining a dual corridor circulation pattern with small animal rooms (~150 sq. ft) in a mouse barrier facility. A single-corridor

circulation pattern in essentially the same layout can increase the mouse housing capacity by 45 percent.
4. Hallways too narrow impeding efficient transport of cage racks to and from animal rooms.

III. ENGINEERING ISSUES

A. HVAC Issues

1. The HVAC system for the animal facility is not sufficiently independent of the HVAC system for the remainder of the building. This precludes the option to conserve energy by shutting down the HVAC system for the remainder of the building when it is not required.
2. During periods of seasonal transitions (heating to cooling and *vice versa*), the HVAC system only provides either cooling or heating capacity. This inevitably results in days when animal room temperatures cannot be maintained within the preset range.
3. Failure to provide redundancy for all essential HVAC components required to maintain design environmental conditions at all times.
4. Automated monitoring and alarming of environmental conditions in the animal rooms and other critical areas not provided.
5. Inadequate ventilation and air conditioning capacity for extremes of outside temperature and humidity.
6. Poor supply air distribution/circulation in room.
7. Air supply and exhaust not balanced properly.
8. Not providing exhaust where needed – e.g., over cage-washer and autoclave doors.
9. Excessive noise from fans and ductwork, especially in rodent facilities.
10. Failure to give adequate consideration to integrating ventilated racks with the building ventilation system. For example, direct exhaust of ventilated cage racks to the facility exhaust system separates the cage (animal) and room (personnel) environments.
11. Failure adequately to seal the room envelope around mechanical, electrical and plumbing perforations, thus confounding efforts to balance the room.
12. Failure to provide a separate sealed, corrosion-resistant, drained air exhaust system for the cage-wash area and cage-washing equipment resulted in the collapse of a ceiling because of water damage from condensed moisture leaking from overhead exhaust ducts.
13. Lack of individual animal room temperature control.
14. Animal resources staff lacking direct control of room temperatures.
15. Using steam reheats for animal room reheats, resulting in wide fluctuations in animal room temperatures.
16. Failure to cool supply air sufficiently to dehumidify outside air.
17. Overkill with use of trim humidifiers.
18. Using solenoid valves for animal room terminal reheats that default in the open position. Failure of these valves may result in overheating the room to levels that are potentially lethal for the animals housed in the room. Animal reheat solenoid valves must default in the closed position.
19. Failure to provide adequate humidification capacity.
20. Failure to cool supply air sufficiently to dehumidify outside air adequately.
21. Access to valves and filters are in animal room ceilings, which requires maintenance personnel to enter the rooms for routine servicing.

B. Plumbing and Related Issues

1. Floors don't slope to drain.
2. Drains too small.
3. Providing drains unsealed drains in rooms where they are not likely to be used, e.g. rodent rooms and corridors in barriers. If floor drains are provided in areas that will not routinely require them, they should be equipped with airtight caps.
4. Lack of floor drains where required.
5. Inadequate water supply and/or drain size when using equipment that disposes of bedding directly into the sanitary sewerage system. Well-designed drainage systems for use with bedding disposal units will use the drain water from the cage-and-rack washer to facilitate flushing the bedding through the sanitary sewage system.
6. Cleaning difficulty caused by animal-room sinks supported with legs on the floor and a drain that goes straight down through the floor rather than sinks being suspended from the wall with all plumbing in the wall.
7. Failure to consider the following features when routine hose-down sanitation is required:
   a. independent circulating temperature-controlled pressurized system for supplying water to all hose bibs
   b. drain troughs in floor with water source at high end
   c. rim and/or trap flush drains
   d. hose reels.
8. Steam pressure and flow rate not matched to equipment; inadequate hot water and steam to run all equipment at the same time (multiple washers/bulk autoclaves).
9. Black steel pipe used for clean steam, resulting in rusting pipes and rust contamination in autoclave chamber.
10. Lack of sinks in or near animal rooms.

C. Electrical/Lighting/Power

1. Light levels too high in rooms housing albino rodents.
2. Light levels too low and/or poorly distributed; dark spots in the animal room created by failing to coordinate the location of lights with the location of racks in the room.
3. Night-lighting (red lights) not provided in animal rooms.

4. Automatic control and cycle monitoring of lights not provided, so no documentation that lights are actually turned on and off at the designated times.
5. Light fixtures not water resistant.
6. No emergency power.
7. Inadequate emergency power – e.g., emergency power is provided for everything except chillers.

IV. ACKNOWLEDGEMENTS

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Section III

Facility Design

A: General

Chapter 18

Animal Care and Administration Space

Robert E. Faith, Mark A. Corey and Rachel Nelan

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I. ANIMAL HOUSING

Animal holding space must be designed to ensure animal well-being, meet research requirements, be cleanable and easily maintained, and minimize experimental variables. Housing areas must promote a healthy social environment for the animals. Decisions on how to house a diverse census of animals must involve consideration of the characteristics of each species.

A. Size and Configuration of Animal Rooms

The configuration (size and shape) of animal rooms varies considerably between facilities and in many cases within facilities. This frequently results from designing rooms for specific species or a group of species, such as mice, rats, cats, rabbits, etc., based on the footprints of the cage racks used to house the various species and the work to be done in the room.

Designing animal rooms around specific types of caging can affect both the length and width of rooms, and can negatively

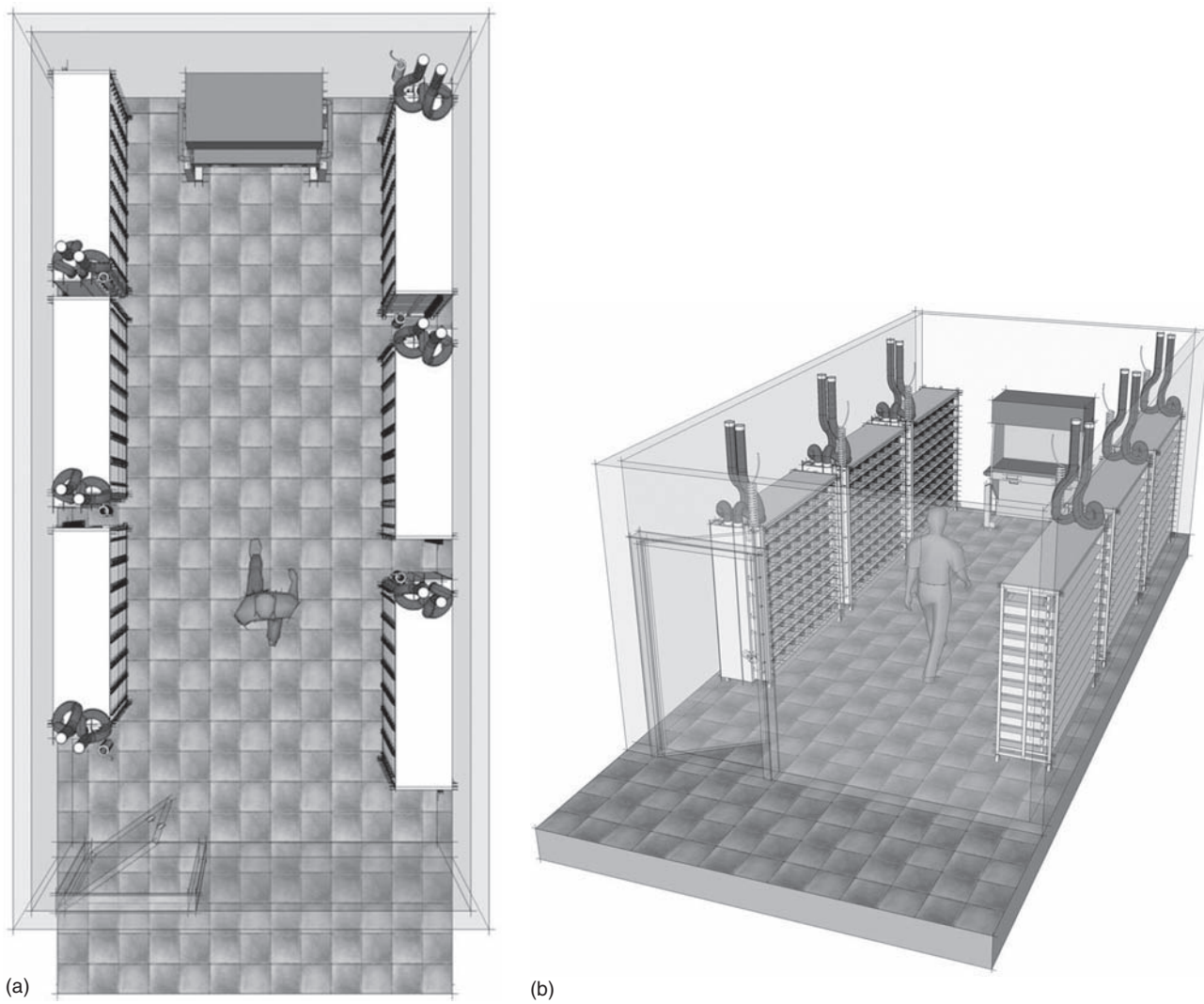


Fig. 18-1 An animal room with single-sided cage racks laid out down the long walls of the room, leaving the center of the room open as a workspace for cage-changing or research manipulations of animals. All cages in the room can be accessed without moving the racks.

impact their flexibility. In some cases, usage requires that there be an anteroom to the animal room, and this also affects configuration. The species of animals, type of caging and racks, and type of research being done will all affect the design of the room. In recent years there has been a trend to design rodent facilities as modular designs. As part of this move there has been a trend to design relatively large rodent rooms (e.g., mouse rooms holding 840 to 1,700 or more mouse cages). This is attractive to institutional administrators because it increases efficiency of design (more cages per square foot of floor space). However, large numbers of cages in a room can be problematic if coupled with many investigators in the room because in the latter case there is often intense competition by various individuals or groups to work there, to the point that both husbandry and research activities can be inhibited. The layout of cage racks in animal rooms may be arranged in several ways (see Figures 18-1–18-4). Since investigative staff spend significant amounts of time working with their animals in the animal rooms, investigator input should be obtained when determining the cage-rack layouts and number of cages for animal rooms.

Animal rooms should be sized so that caging and associated husbandry equipment is not crowded and there is sufficient space for husbandry and research procedures to be accomplished efficiently. The species to be housed in the room may impact the size of the room. For example, nonhuman primate rooms should be sufficiently sized so that animals can be readily observed in their cages but observers can remain far enough away from the cages to be out of reach of the inhabitants. Access to cleaning equipment and floor drains should not be inhibited by caging. In large animal rooms that have a water source and floor drains, the rooms may be larger to allow access to trench drains for cleaning purposes. Rodent rooms should be sized to provide space for the placement of

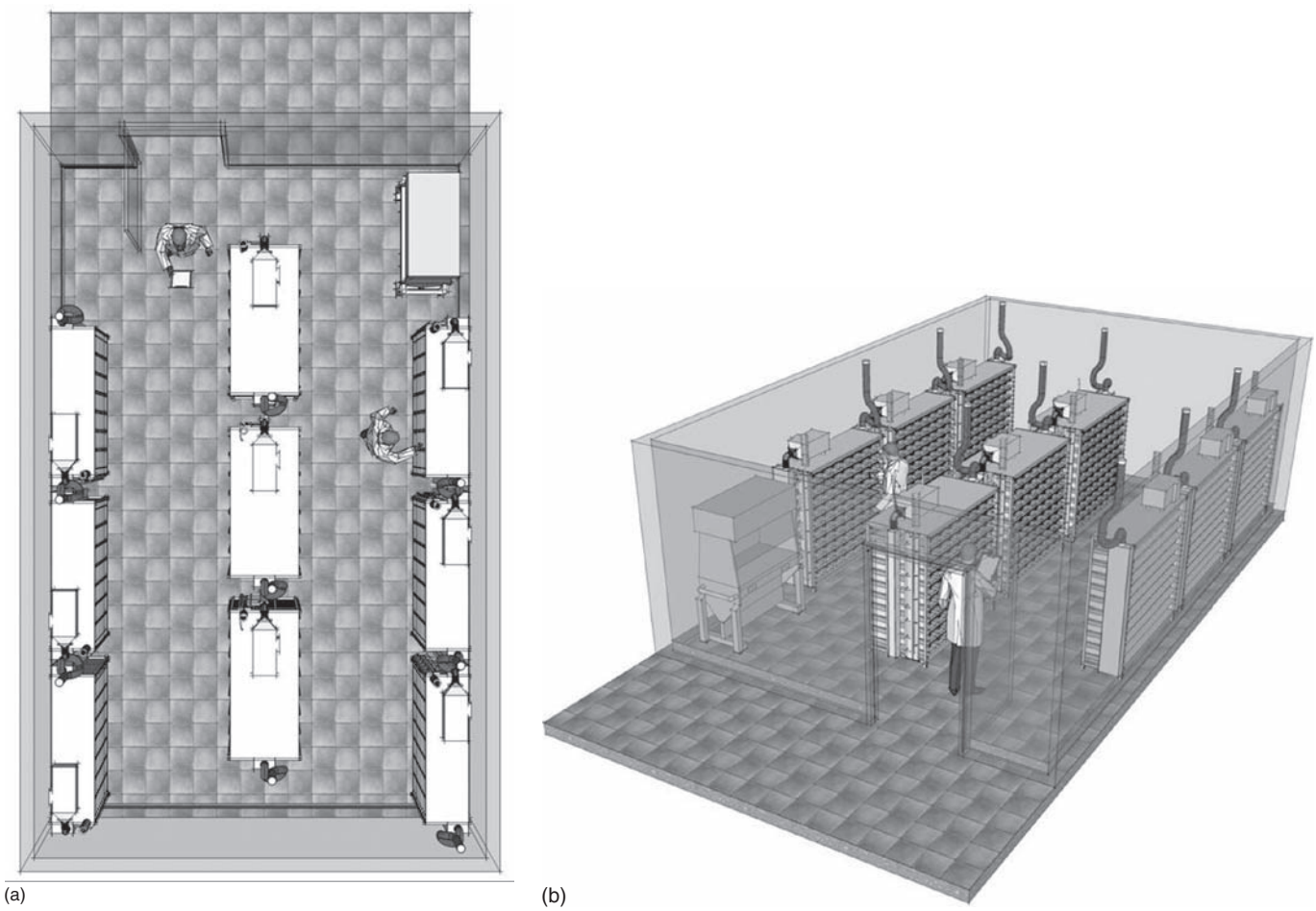


Fig. 18-2 A larger animal room with single-sided cage racks laid out down the long walls of the room and double-sided racks down the center of the room, leaving two aisles providing workspace for cage-changing or research manipulations of animals. All cages in the room can be accessed without moving the racks.

racks with a large enough workspace around them to allow husbandry and research procedures to be performed without having to move the racks. Where micro-isolator caging is used for rodent housing, the aisles between cage racks should be wide enough to allow easy passage of laminar flow workstations.

B. Caging and its Influence on Room Design

The caging system should be carefully designed to facilitate animal well-being, meet research requirements, and minimize experimental variables. Cages should be isolated from heat, vibration, and noise sources. They should provide an escape-proof enclosure with a comfortable environment that confines animals safely with easy access to food, water, and ventilation, and provides adequate space to permit freedom of movement and normal postural adjustments. Because of the significant impact caging has on animal room design, and the differences in design of each caging system, it is desirable to identify the cage design and acceptable vendors early in the planning process.

C. Flexibility

The Merriam-Webster Online Dictionary defines flexibility as characterized by a ready capability to adapt to new, different, or changing requirements. This is a very desirable characteristic for a modern research animal facility. It is virtually impossible to predict what the future will bring for animal-based research. A sudden new technological discovery could lead to a significant change in research programs and/or the preferred subject species, thus requiring a change in use of the facility. The construction and renovation cost of the modern research animal facility is quite high. Therefore, maximizing the flexibility of the facility in design should result in a facility that will easily adapt to changing research needs.

Flexibility comes from building in provisions that will accommodate future changes. An assessment of the possible or probable frequency of change is required to determine the type of flexibility to be provided. Cost is a major driver for decisions on types and extent of flexibility. Types of flexibility include adaptability, versatility, interchangeability and

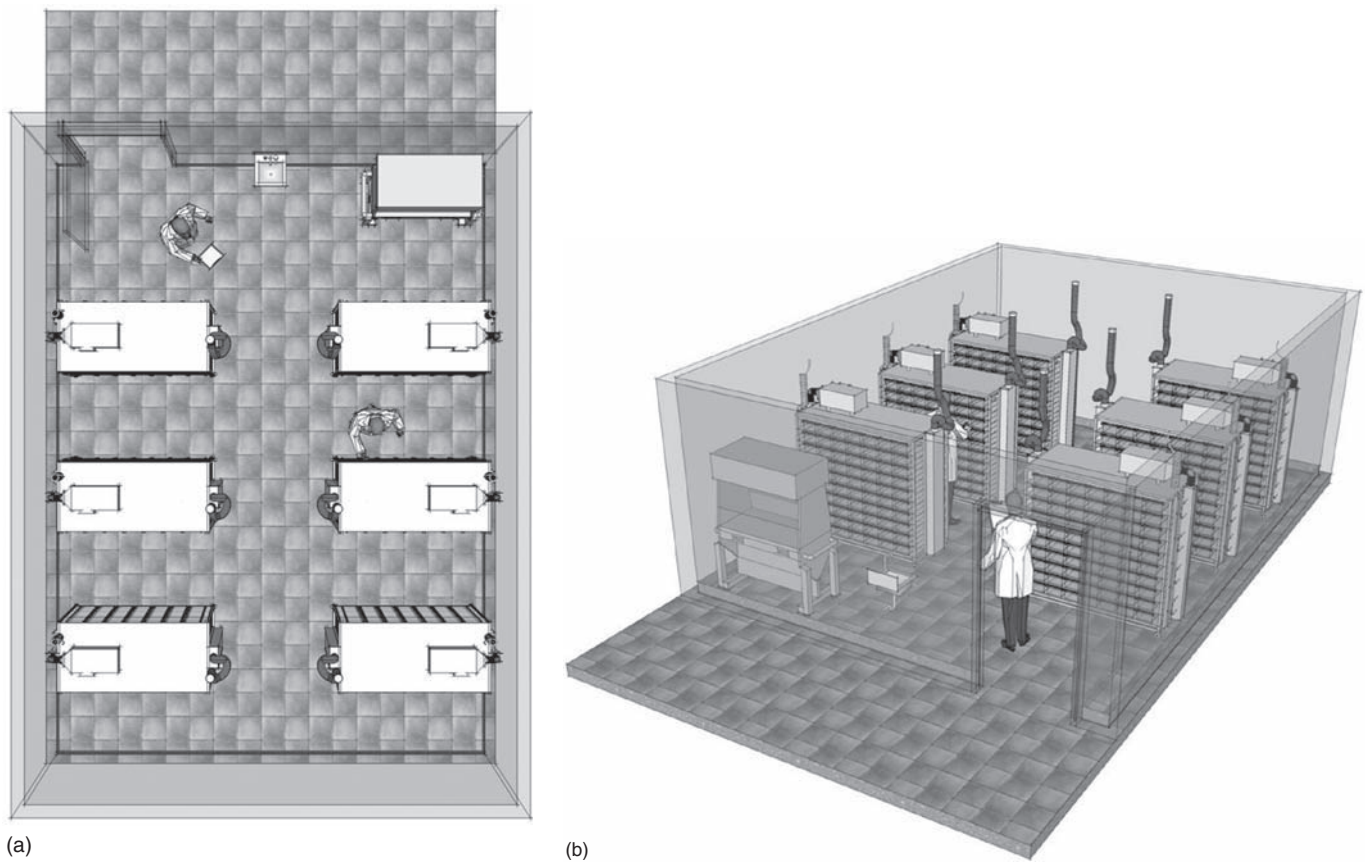


Fig. 18-3 An animal room with double-sided cage racks laid out library style. While this arrangement may increase the total number of cages in the room, the racks frequently have to be moved for full access to the cages.

expansibility. *Adaptability* refers to the ability to meet changing requirements. An adaptable facility has a physical plant that can accommodate required changes in ventilation rate, temperature, humidity, light cycles and power. The ability to rearrange items within a space is *versatility*. In an animal facility, these items would be caging systems, racks, runs and/or other animal-care related equipment. The ability to change a procedure room into an animal holding room or *vice versa* is another form of versatility. This type of versatility is frequently built into facilities where the modular design incorporates a number of animal holding suites. *Interchangeability* is the ability to change components with a minimum number of parts and the least amount of storage space required. As the name implies, *expandability* is the ability to enlarge. This may be a single room or the entire facility. The ability to expand an entire facility requires that the initial mechanical systems be oversized or be designed to be easily expanded in capacity in the future. Flexibility can also be enhanced by designs that do not box in special facilities such as biocontainment, barriers and surgery. Provision of an avenue to expand, via conversion of animal rooms or other space that can be incorporated into the special facility, will allow expansion of these high-cost facilities with minimal expense.

Perhaps the most flexible animal room is a plain, empty box; a room with nothing attached to or projecting from the walls, ceiling or floor. A room such as this allows for varied uses, depending on what equipment is moved into it. It can be used to house species ranging from mice or other rodents to large animals. This is accomplished by using the appropriate caging system for each species. Rodents can be housed in cages ranging from open wire or plastic cages on mobile shelf-units to individually ventilated cages on racks with integral HEPA blower units. Cages for other species, such as guinea pigs, rabbits, cats, non-human primates, etc., are simply placed in the room for housing these species. Larger species, such as dogs, or small farm species may be housed in free-standing runs using a dry bedding system.

In contrast, the more structure there is built into a room, the less flexible the room becomes. For example, built-in, hard-walled large animal runs in a room generally make the room unsuitable for housing anything but large animal species without undergoing major renovation. Even something as simple as floors sloped to drains may make the use of mobile racks in a room difficult because they tend to roll to the low area. On the other hand, the installation of floor drains in flat-floored rodent

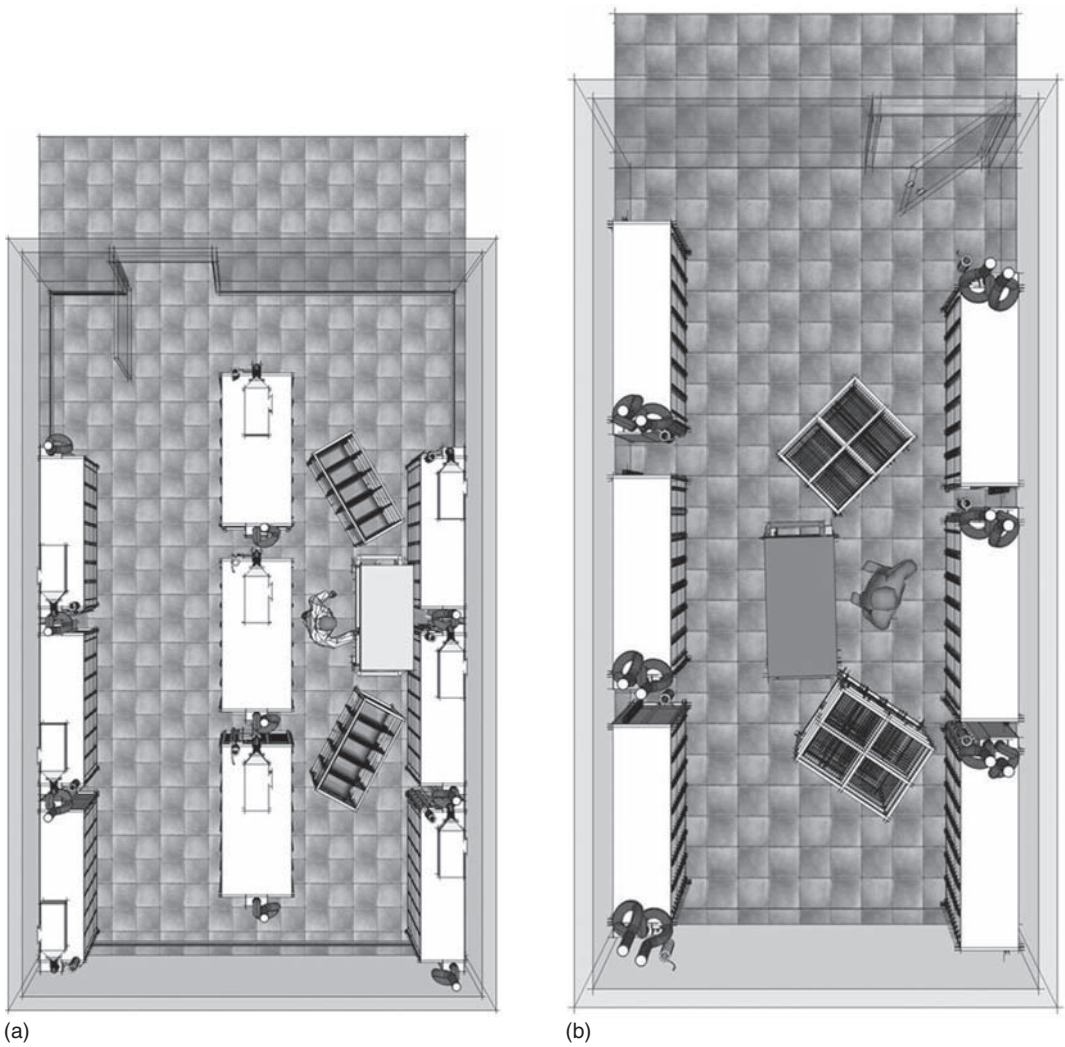
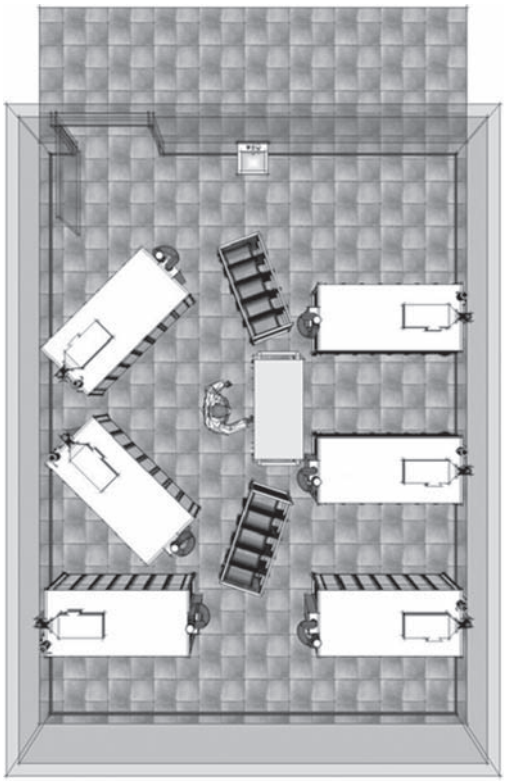


Fig. 18-4 Cage-changing in the three types of rooms shown in Figures 18-1–18-3. In the larger room (b), cages can be changed in one aisle of the room, leaving the other aisle open and thus allowing investigator access to animals in the open aisle. The library-style layout.

rooms does not interfere with the placement of mobile racks in the room, but may make the room more suitable for housing other species, such as non-human primates or canines, in the future. An alternative would be to provide the room with narrow drain troughs on the sides of the room. The troughs should be steeply sloped to drain and the floors should be moderately sloped (1/16–1/8″ per foot) from a crown in the center of the room to the troughs. In this case, mobile racks should be equipped with locking casters (see Figure 18-5). Another trend is to design rooms by species and by size – small animal versus large animal. This will provide a great degree of flexibility, but not universal flexibility. Designing holding rooms to handle all types of species will include some compromises at either end of the spectrum. Rooms will either be difficult to clean for large animals, or they will have sloped floors which makes moving small-animal racks challenging. Careful thought should go into the housing and operations of holding rooms when considering the issue of flexibility.

Recent changes in rodent rack design have enhanced the ability to design and build flexible rodent rooms. Mouse and rat racks with very similar footprints are now available, allowing for the design of rooms equally suited for housing either species. When designing the animal room, if the cage-rack footprints of the various racks used for housing the common species are kept in mind it is not difficult to design rooms sized to adequately house a variety of the commonly used species. One thing to keep in mind, though, is that there are many types of ventilated racks, further complicated by the myriad of options to connect (or not to connect) them to the building mechanical system (see Figure 18-6). The options consist of HEPA fan units mounted on the racks, fan units mounted on the walls, floor-mounted fan units, direct connections of the



(c)

Fig. 18-4 (Continued) (c) requires racks to be moved for cage-changing.

rack supply and exhaust to the building, and fan units located in interstitial spaces connecting many racks. These options need to be investigated and resolved, as they can have a profound impact on the room layout and flexibility, as well as the cost of the project (see Chapter 20).

One approach to achieving flexibility is the addition of services (plumbing, electrical, voice/data, environmental monitoring, etc.) to the plain room. Such services could include anything that may be conceived to be needed to enhance animal housing/husbandry of various species and/or the ability of the research staff to easily gather data and work with their subject animals. The installation of above-ceiling blowers for supplying air to ventilated racks with the racks directly connected to house exhaust is less costly than individual rack-mounted supply and exhaust blowers. When the room is not being used for ventilated racks, the HVAC system reverts to a normal supply and exhaust situation and the rack connections do not interfere with the use of other equipment in the room (see Figure 18-7).

This arrangement has the advantage of removing the noise, vibration and heat loads of the fans from the room, plus the heat and smell from the animals. The provision for voice/data connection (wired, wireless, or both) allows for real-time data collection by both the investigative and husbandry staffs. Animal rooms can be plumbed to allow the use of portable

(a)

(b)

Fig. 18-5 A room equipped with free-standing dog runs: (a) the runs; (b) the trench drain at the back of a run. This room can easily be converted to another use by disassembling the runs, moving them to storage, and moving other caging equipment into the room.

(a)

(b)

Fig. 18-6 Two examples of the various ways to supply and exhaust air to ventilated racks: (a) a rack with rack-mounted supply and exhaust blowers: (b) racks with above-ceiling air supply and exhaust directly connected to house exhaust.

(a)

(b)

Fig. 18-7 The versatility of above-ceiling supply and exhaust for ventilated racks: (a) ventilated racks are in place and coupled to above-ceiling supply and exhaust; (b) the racks have been removed and all that remains are the ceiling couplings for supply and exhaust. The room can be converted to other uses by moving the appropriate equipment into it.

sinks. Thus there can be a sink in the room when needed, but the sink can be removed and not in the way when not needed (see Figure 18-8). This is often accompanied by a capped floor drain.

Flexibility should be maximized as much as possible. This will result in a facility that lends itself easily to being adapted to meet the requirements of changing research needs. To design and build flexibility into the facility may result in an increase in the initial cost of the facility, especially if flexibility is achieved by adding services that will not be used all of the time. However, building flexibility into the facility will allow changes in research focus to be readily accommodated.

D. Species Grouping/Separation

As a general rule, different species should be housed separately in their own rooms. The *Guide for the Care and Use of Laboratory Animals* (the *Guide*; ILAR, 1996) recommends this "to prevent interspecies disease transmission and to eliminate anxiety and possible physiologic and behavioral changes due to interspecies conflict." Other methods may be used to accomplish species separation when small numbers of animals are involved. Various types of housing equipment, such as cubicles, laminar-flow units, and cages with filtered air or separate ventilation (see Chapter 20) may be used to separate

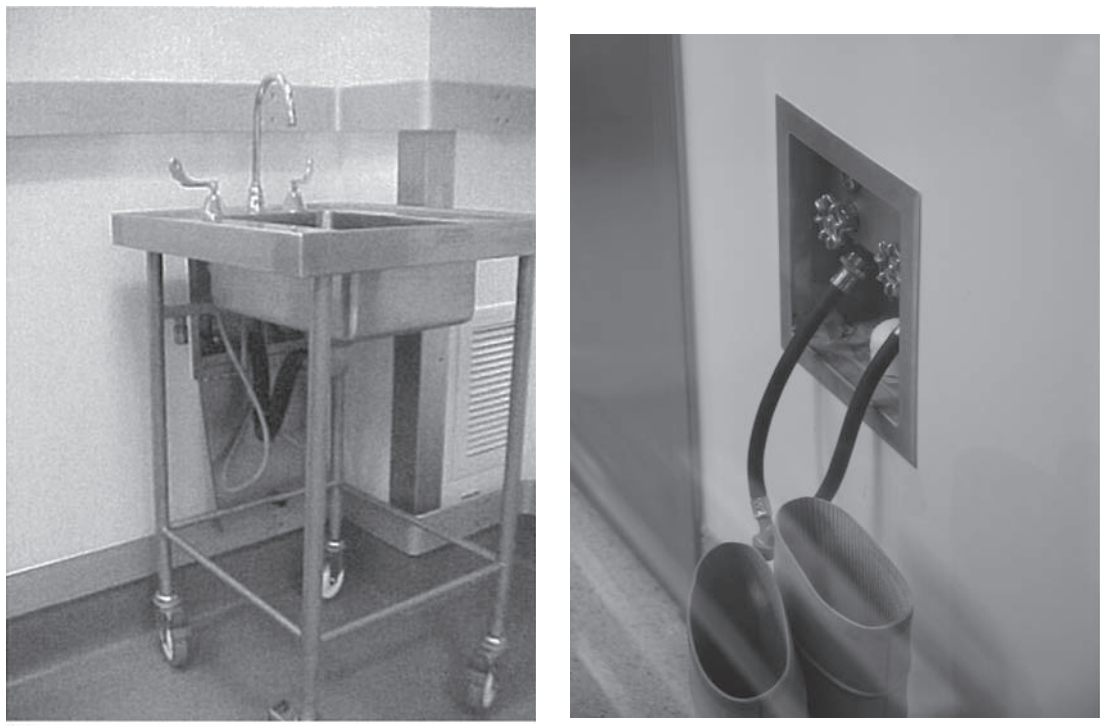


Fig. 18-8 Flexibility afforded by providing plumbing for portable sinks: (a) a portable sink connected to the plumbing; (b) the plumbing without the sink connected. This allows for the use of a sink in the room when needed, without having a permanently mounted sink there.

small numbers of different species in the same room. In instances where two species have similar pathogen status and are behaviorally compatible, it might be acceptable to house them in the same room.

E. Types of Holding Rooms

Animal room types are often defined by the species size (large or small), whether they are wet or dry, or by function (conventional, barrier, containment). Large species rooms would include canines, primates, sheep, etc., small species rooms typically mean rodents. Rabbits can be defined in either case. The notion of large or small species rooms will often define the size and the infrastructure for each room. Large species rooms are often just that – larger – since the caging required for these species takes up more floor space. The room sizes are still driven by the population of the room. Small species rooms vary greatly in size pending the population.

1. *Wet or Dry*

The other definition, wet or dry, simply means that rooms may be provided with hot and cold water and drainage, or there is no plumbing service in the room. There is a trend for small species rooms to be dry, but in many cases these rooms are fitted out with either sinks or in-wall plumbing boxes to allow for portable sink usage. Some are even fitted out with capped floor drains for future flexibility. Large animal rooms are usually wet. In many cases, large animal rooms have hose bibs and trench drains to facilitate the cleaning process. To work most effectively floor drains require sloped floors, which can be problematic in rooms where mobile racks are used to house animals. Therefore, rodent rooms frequently have flat floors and do not include floor drains. Large animals may be effectively and efficiently cared for using dry systems where there are no floor drains. Flat floors make a room more flexible than do sloped floors.

It is important to remember, when designing holding rooms for a specific use, that a major shift in research emphasis may require significant renovation for the animal rooms to meet the new requirements. Renovations inside vivariums with ongoing operations can be expensive and disruptive. These issues are driving facilities to be designed as generically as possible.

2. *Conventional Holding*

The majority of animal housing space found in research animal facilities is space that would be considered conventional. This is space that has no special provisions for keeping infectious or hazardous agents *contained in* or *excluded from* the space.

Fig. 18-9 The gowning area for entry into a barrier. Lockers are seen in the foreground and a shower is in the back right. In the center of the picture is a step-over bench where shoe coverings are donned, and beyond that is the air-shower entry into the barrier.

3. *Barrier Holding*

Barrier housing areas are designed and operated to prevent the inadvertent introduction of infectious agents and specific pathogens. Barrier housing areas should be designed so they can be easily isolated from other areas of the facility. Services to barriers, such as ventilation, water, compressed air, vacuum, etc., should be installed in a manner to prevent cross-contamination between the barrier and other areas of the facility. For ventilation, this may entail a separate air handler and/or HEPA filtration of the supply air. It is advisable to HEPA filter the supply air for barrier areas, either at the air-handling unit or at the rack. It is felt by some that HEPA filtering of supply air to barriers is unnecessary and not cost-effective, and that it is highly unlikely that airborne infectious agents would enter a facility via the ventilation system when the facility is ventilated with 100 percent fresh air filtered at the 95 percent level. Task filtering, such as with ventilated racks, may be used to control airborne agents that enter the facility by routes other than the ventilation system. Lines for water, compressed air, vacuum, etc., should have filters installed to prevent cross-contamination with other areas of the facility. Ideally, these systems should be separate from other parts of the facility. Barriers should be located out of general traffic patterns in the facility. Entry of personnel and supplies should follow strict protocols to prevent the entry of pathogens into the barrier colonies (see Figure 18-9; also Chapters 20 and 24 in this book).

4. *Containment Holding*

Containment areas are designed and operated to provide containment of hazardous agents (infectious agents, toxic chemicals and carcinogens). These areas should be out of the main traffic patterns of the facility. Services to containment housing areas, such as ventilation, water, compressed air, vacuum, etc., should be installed in a manner to prevent cross-contamination between the containment area and other areas of the facility. For ventilation, this may entail a separate air handler. Exhaust air should be HEPA filtered or otherwise treated to prevent release of hazardous agents into the atmosphere. Piping for water, compressed air, vacuum, etc., should have filters installed to prevent cross-contamination with other areas of the facility. The level of containment to be provided by the facility is dependent on the hazard level of the agent(s) to be used in the facility. The hazard levels range from Animal Biosafety Level 2 (ABSL2) to Animal Biosafety Level 4 (ABSL4). The facility requirements for the various hazard levels tend to change with time, so current requirements should be determined during design. The *BMBL* (CDC/NIH, 2007), published by the Centers for Disease Control, provides guidelines on facility requirements at the various hazard levels. Entry and exit of personnel and supplies should follow strict protocols to provide for personnel safety and prevent the movement of hazardous agents from the containment area. Provisions must be made for the decontamination of supplies and equipment before they are moved from the containment area to "clean areas" (see Chapter 25 in this book).

5. *Quarantine Housing Areas*

The *Guide* (ILAR, 1996) defines quarantine as "the separation of newly received animals from those already in the facility until the health and possibly microbial status of the newly received animals have been determined." The quarantine housing area should be located to allow complete separation of the animals in quarantine from resident colonies. Ideally, quarantine should be performed as a separate program. Provision should be made for decontamination of supplies and equipment before they are moved from the quarantine area to "clean areas." If this cannot be done, provision must be made to transport contaminated material to a decontaminated site in sealed containers. Personnel, material and animal traffic patterns should always be from clean to dirty. If staff must move from the quarantine area to clean areas, provision must be made for the use of appropriate personal protective equipment (PPE) or showering and donning clean clothing before entering the resident colonies. At times it may become necessary to quarantine animals from resident colonies because of a disease outbreak. This may be accomplished by moving animals from the resident colonies to the quarantine area, or by placing an entire room in the resident colonies under quarantine. In the latter case, it is necessary to be able to control personnel traffic into the room. At the minimum, this requires that the room be equipped with a door lock. If the quarantine program is large and ongoing, thought should be given to locating the quarantine areas off-site, or at least in a location remote from the resident colonies (see Chapter 26 in this book).

6. *Cubicles*

Cubicles are small, self-contained rooms that are usually sized to contain one or two racks of animal cages. They are generally rooms within a suite of rooms. These small rooms may be either positively or negatively pressurized to the surrounding spaces, depending on their intended use. They frequently have guillotine-type doors with full-vision panels, and can have integral lights and HVAC systems if desired. They can be field-constructed or provided prefabricated. These rooms lend themselves to small studies, quarantine, small containment facilities, or housing diverse species within the same area. A number of cubicles will fit in the same square footage as a standard animal room, providing flexibility to the space (see Chapter 15 in this book).

F. Room Relationships and Layout of the Facility

Animal rooms should be located in areas that are easily accessible to husbandry and research staff, but are remote or isolated by physical means from noisy areas such as cage-wash facilities or high-traffic areas. Many species are stressed by loud noises and/or by high traffic. Those species that produce relatively little noise (such as rats and mice) should be isolated from species producing significant noise levels (such as dogs and non-human primates). There are currently no quantitative standards for sound intensity and frequency (noise) levels in research animal facilities or animal rooms, and it would be advantageous for the industry to adopt such standards. For animal rooms, the standards should be species-specific. In the absence of standards, it is recommended that ambient sound intensity levels not exceed 50 dB. Additionally, consideration should be given to sound frequency, as some species (such as rodents) hear at high frequency, beyond that of human capability.

Holding rooms can be arranged in several ways, but there are generally two ways to lay out holding rooms in the facility. One is to have rooms located directly off primary corridors, and the other is to arrange them in suites (Figure 18-10). In the first instance, rooms are easily accessed and quite flexible. If holding rooms and procedure spaces are similar in size and carefully designed, then this type of arrangement can provide a great deal of flexibility. This layout has to be carefully coordinated with the structural grid. If there are laboratories above, then care should be taken to understand the structural grid limitations and how that affects the locations of partitions and room sizes in the vivarium. Ideally, columns are located adjacent to partitions. In some cases, partition thicknesses can be increased to hide the column intrusion into the room, but this will increase the facility size or decrease the usable area of the rooms. With rooms off the corridor, security, equipment traffic noise and biosafety concerns can be an issue. One option is to add anterooms. Procedure rooms located adjacent are typically not dedicated to any type of research, and therefore can be designed to be flexible and accessible to several researchers.

The second instance is to provide a series of holding rooms and procedure space within a suite. This provides an additional door between the holding room and the primary corridor, thus allowing for additional security, biosafety and noise control. In this case, the suites are often perpendicular to the building structure, which will have to be carefully coordinated. Suites are often generic in nature and repetitive, allowing a great deal of flexibility for the facility. The suite corridor will serve as staging space for racks and equipment, allowing the primary corridors to remain free for traffic. These suite corridors often have integral sinks and janitor's closets in them. Suite design allows for a diversity of species, for the inclusion of barrier or containment space, and for quarantine within a modular and repetitive design, which makes them more economical to construct and operate.

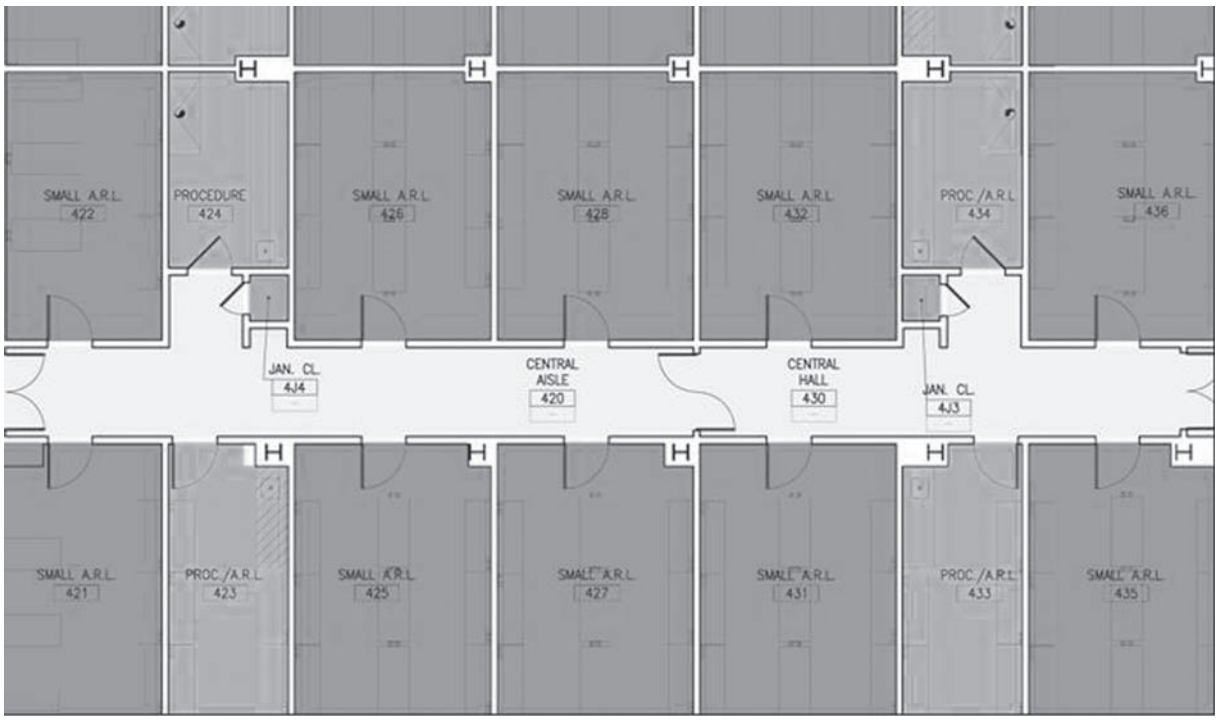
II. ANIMAL-CARE SUPPORT SPACE

A. Receiving/Shipping

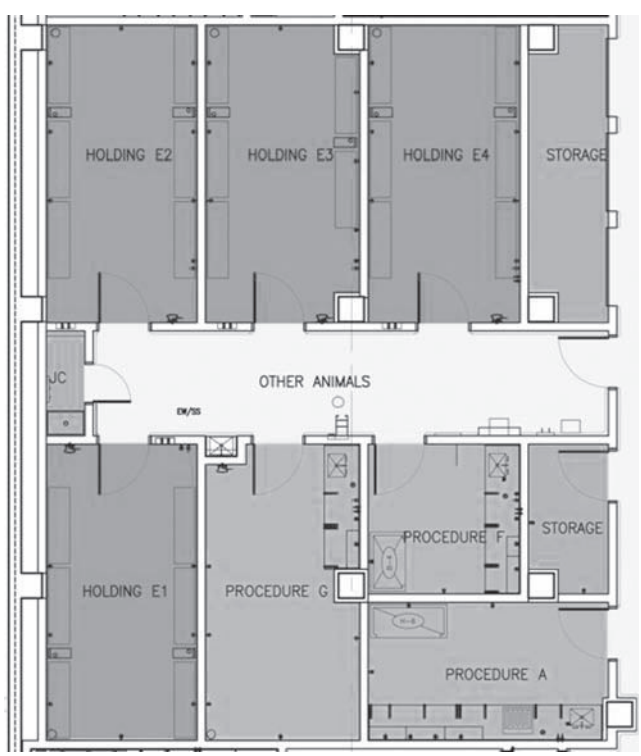
Animals and animal-care supplies should be received at a dedicated loading dock. The dock size will vary depending on the size and animal population of the facility: small facilities will have relatively small docks, while large facilities may have fairly extensive docks. The dock frequently serves as the route for the outgoing waste stream, as well as receiving animals and supplies. Provision should be made for the separation of clean and dirty items. In large facilities this separation may result in separate clean and soiled docks; in smaller facilities there may be separate clean and soiled areas on a single dock (see Chapter 9 in this book).

Depending upon the site and facility, the truck space at the dock may be enclosed for security concerns, shielding the nature of the material from neighboring facilities.

Often, a number of activities occur on the dock. These may include processing incoming animal shipments, processing outgoing shipments, receiving supplies, supply storage, and waste storage prior to its removal. The procedures used for processing incoming animals may vary from simple inspection of the animals before transferring them to their homeroom, to uncrating incoming rodents and placing them in clean caging before transporting them to their homeroom. With the extensive use of disease-free rodents, processing generally consists of uncrating and inspecting them in a laminar flow workstation and placing them in clean cages in the workstation. This requires space on the dock dedicated to this function, space for the workstation(s) and staging space for the incoming animal crates, clean caging, and supplies. Processing of large animals may include the need for bathing the animals before they enter the facility proper. It is advantageous to have a room (or rooms) for short-term animal holding on the dock. This provides a place for overnight holding of animals that arrive late



(a)



(b)

Fig. 18-10 (a) Illustration of animal rooms located directly off a primary corridor; (b) illustration of a suite of animal and procedure rooms.

in the afternoon or for holding animals from a shipment that must be verified as to the animals' health status. This is also a convenient space for institutions where a single dock serves multiple facilities.

The development of transgenic rodents has not only led to large rodent populations at a number of institutions; it has also resulted in a significant amount of animal shipments from research institutions as researchers share various genetic

constructs or ship animals for storage in central embryo banks. The preparation of animals for shipment frequently takes place on the dock. Provision should be made for a space for this function, as well as space for holding outgoing animals until the shipper picks them up.

Frequently, supplies are stored on the dock as well as received there. This may necessitate areas for storage or staging of feed, bedding and expendable supplies. Cage-wash chemicals are often available in bulk totes that are frequently located on or close to the receiving dock for ease of handling. This is desirable, as it eliminates or reduces the movement of hazardous materials throughout the facility. The chemicals can be piped directly to the washing equipment from this remote location. If plans include the use of bulk cage-wash chemicals, space must be made available for their storage, and must include accommodations for leak containment and meet any local code requirements for hazardous materials.

B. Cage Processing

Cage-wash is the center of circulation for cages; therefore, it should be located as convenient as is practical to animal housing areas or elevators leading from housing areas in multi-level facilities (see Chapter 9 in this book). Cage-wash areas are noisy, and noise abatement should be considered if cage-wash is located adjacent to housing areas. Cage-wash areas are normally separated into soiled and clean sides. Soiled caging is brought into the soiled side of cage-wash and processed through cage-washing equipment. The processing of dirty cages through cage and rack washers creates a hot, humid environment in the cage-wash room, and ventilation for the cage-wash area requires special attention. Appropriate exhaust capacity through the use of exhaust (canopy) hoods should be provided over all cage, rack, bottle and tunnel washers, regardless of any exhaust built into the washers themselves or provided elsewhere in the room. They should also be provided above any autoclaves. The intent is to exhaust any escaped moisture and steam immediately when the equipment doors are opened, thus preventing damage to the surrounding finishes and providing a more appropriate working environment. The entire cage-wash facility should have a high ventilation rate with cool air to exhaust the humidity and for personnel comfort. Since the cage-wash area is a high-humidity area, condensation can be expected in the exhaust ducts. Provision should be made for preventing condensation and any draining that does occur. Exhaust ducts for cage-wash areas should be constructed from rust-resistant materials such as stainless steel.

The soiled side of cage-wash should provide space for staging dirty equipment, breaking down cages, draining water bottles, removing soiled bedding, and loading cages and racks into the dirty side of the processing equipment (Figure 18-11). Often there is a scullery sink for hand-washing special equipment, an ultrasonic cleaner for small parts, an area for cage repair, and a laundry for the processing of reusable gowns. In rodent facilities, cage-wash rooms are typically operated in a drier fashion than in facilities with multiple species. In multiple species facilities, there is often an area for hosing down cage racks with high-pressure hose stations. Floor drains and drip-off pits are required regardless of the facility type.

There should be sufficient space on the clean side to remove the sanitized cages and racks from the washing equipment, place clean bedding (and sometimes feed) in the cages, reassemble the cages, fill water bottles, and stage the clean cages for transport to animal rooms or storage areas or for processing through autoclaves for sterilization. The material-handling

(a) (b)

Fig. 18-11 Load (dirty) and unload (clean) sides of a cage-wash area. (a) The load end of two tunnel washers, one of which is automated. (b) The unload end of the automated tunnel washer. The unload robot and the automatic bedding dispenser can be seen in this picture.

process in cage-wash should be studied thoroughly, as it has profound impacts on the space required in cage-wash, material-handling equipment, and protocols for cage-changing. In particular, the decision of where the cages are assembled should be determined early on in the design process. Space may also be needed for ancillary equipment such as sinks, bottle washers and bottle fillers.

Cage-processing equipment is manufactured by a number of companies. Buyer guides published by several laboratory animal trade magazines provide contact information for these manufacturers. The equipment is available in various sizes and shapes, from small cabinet washers to large rack-washers that will wash several racks at once, and large tunnel washers that can process hundreds of cages per hour. Some vendors have developed equipment that will reduce the utility consumption and improve the processing time, which can result in less equipment and lower operating costs. Care should be taken when sizing and choosing this equipment. A detailed throughput analysis should be carried out to understand what kinds of equipment will be required, and how much labor it will take to operate it. The sizes of the equipment vary greatly, which will affect the layout of the space. Some of this equipment can be associated with robots that automate some or all the functions done by personnel. Additionally, automatic bedding dispensers can be associated with the clean side of tunnel washers to automatically bed clean cages. Semi-automated bedding removal systems are available, which removes the staff from repetitive motion exposure and improves allergen control. There is a variety of these systems out there, each with its own unique requirements.

The quality of steam provided for autoclaves and the heating of water can be an issue. Water for steam-generating boilers is often treated with rust inhibitors and water softeners to prolong the life of the boiler in many institutions. If steam treated with these chemicals is directly injected into the process water, it will leave a residue on equipment processed through the washers. This is undesirable. These chemicals will hasten the breakdown of polycarbonate plastics. Steam generated with R/O water is ideal for use in cage-wash areas.

The selection of the cage-wash equipment depends on the types and volume of equipment to be washed. This equipment may require very large utility services, including high-voltage, multiphase electrical sources, high temperature, high-volume water, compressed air, and large volumes of steam – sometimes at high pressures.

The layout of the cage-wash area is dependent on the equipment to be used for cage processing and the type and volume of the animal-care equipment to be processed. The layout should provide ample room to house the equipment and space for all of the functions mentioned above. Space may also be required for one or more bulk autoclaves or decontamination chambers, if caging is to be sterilized before being used. If the cage-wash equipment is to be fitted with robots, the space requirements need to be increased. Cage-wash equipment should be selected early in the project to insure that pit sizes are correct, utilities are adequate and appropriate space is allowed for the equipment. Separation walls are recommended to isolate the clean and dirty sides of cage-wash, as well as the mechanical and maintenance areas for the equipment. This area should be accessible, environmentally controlled, and lit properly to allow for an appropriate working environment. Sometimes cage-wash equipment detergents are stored in these spaces. Ceilings are recommended above all of this equipment, to avoid warm, moist air penetrating into the rest of the facility.

There are staging and storage needs associated with cage-wash. These include clean-cage and equipment storage and bedding storage. Clean cages and related equipment are frequently stored for short periods on the clean side of the cage-wash room. Space should be provided for the storage of at least 1 day's cage-change on the clean side of the cage-wash room unless dedicated clean-cage storage is provided elsewhere. An alternative is to provide a separate room for the storage of clean caging. Clean-cage storage must be an area where clean caging and equipment will not be contaminated by contact with dirty equipment or waste. Sterile staging should be provided on the sterile side of the autoclaves as well.

Since in normal operation cages are filled with clean bedding in the clean cage-wash area, bedding storage should be adjacent to or close to the clean side of cage-wash. When bedding dispensers are used, there are systems available to deliver bedding to the dispensers from a remote location. Bedding is available in bulk totes of about 1,000 pounds each. This, coupled with the delivery systems, allows bedding to be stored in an area on the loading dock and be automatically delivered from the dock to the bedding dispensers. Storage areas for bedding should be clean, dry and vermin-proof, and sized for between 1 and 2 weeks' of bedding supply. Bedding storage rooms should be located closely to clean cage-wash to facilitate the movement of bedding to the cage-filling equipment.

C. Feed Storage

Feed should be stored in a dedicated room, which is clean, dry, climate-controlled, vermin-proof and easily sanitizable. Feed storage should be located close to clean cage-wash to facilitate the movement of feed to the area where cages will be filled. These rooms should be sized to house from 1 to 2 weeks' of food. There is often a variety of food types in facilities, requiring different types of storage racks or shelving. Rooms should be sized to allow for space behind any storage racks for inspection, or the storage racks should be mobile. All food must be stored on pallets or storage racks which keep the food off of the floor. The room should have the capacity to be kept cooler than the surrounding area, to avoid spoilage and control vermin. Walk-in cold rooms are a good option for bulk feed storage. In large facilities, it is helpful to have several

small storage rooms for feed scattered through the facility. Non-human primate colonies may require fresh produce storage with access to a preparatory kitchen space for dietary enrichment. There are some systems available in other industries that deliver and dispense feed automatically, although this is fairly new for this industry.

D. Dry Supply Storage

There is a considerable amount of consumables used in the modern animal facility. These supplies include disposable caps, masks, gowns, gloves and shoe-covers. For economical reasons, these supplies are usually purchased in bulk, necessitating an adequate amount of storage space. These storage spaces should be clean, dry and vermin-proof. Ideally, the storage areas should be close to the areas of use of the supplies, which means there might be several of these rooms spread throughout the facility. Large programs may have a remote storage area for bulk storage of these supplies, with satellite storage areas near the point of use. Secure storage may be required for items such as syringes or controlled substances. Given the cost of constructing these facilities, consideration should be given to off-site storage of material that is in rotational usage, or for long-term storage.

E. Waste Storage and Removal

Large amounts of waste are generated in the modern animal research facility, and this may require short-term staging prior to entering the waste stream. Most liquid waste generated in the facility goes directly to the sewage system, so the drain system should be appropriately sized to handle large volumes. Liquid waste that must be treated normally enters treatment tanks before entering the sewage system. Most trash generated in the facility is generally taken to a dumpster the day it is generated. Rodent facilities generate large amounts of waste bedding, which is taken either manually to a dumpster or on an automated bedding system which will automatically transport the soiled bedding to a dumpster. Even though waste is not normally stored in the facility, it is valuable to have an area on the soiled dock or on the soiled side of the dock for short-term staging of waste.

Recycling may be required in some jurisdictions or institutions, so space may be dedicated at the waste dock area for recycling containers. This may also mean a variety of these containers will be located throughout the facility. These should be carefully located to control contamination.

Animal carcasses are part of the waste stream from the facility. Carcasses frequently have to be stored before they are incinerated, processed in a tissue digester, or removed from the facility for off-site incineration or burial in a landfill. Carcasses are normally stored in refrigerators or freezers. In facilities where animal carcasses are disposed of by transport off-site, either by the institution or by a contractor, it is helpful to have freezer capacity on the soiled dock for carcass storage prior to pick-up. A walk-in freezer may be required in facilities where large volumes of animal carcasses are generated. Where necropsy facilities are provided, carcasses are often placed in refrigerators adjacent to the necropsy room.

F. Housekeeping

The use of housekeeping supplies and equipment is part of everyday life in the animal facility, and there must be provision for these. In many facilities, dedicated equipment such as brooms, mops and buckets are stored in the animal room, along with small amounts of cleaning supplies. In this case there must be storage space for extra equipment and bulk supplies. This may be accomplished by the use of a central storage room or janitor's closets distributed throughout the facility. Even when a central storage area is used, there should be some janitorial closets in the facility for storage of equipment and supplies used to clean corridors and support spaces.

In larger facilities, it is common to see walk-behind floor-cleaning equipment. This equipment will require dedicated storage space with a floor drain and a hose bib for maintaining the equipment and for charging the battery.

III. ADMINISTRATIVE AND PERSONNEL SUPPORT SPACE

A. Location

Administrative space should be located in an area accessible to animal-care staff, investigative and administrative staff of the institution, and sales and service individuals from outside the institution. It may be located adjacent to animal-care space or remote from it. There should be a realistic needs analysis to determine the amount of administrative space required. Realization that regulatory demands for documentation and "paper trails" are likely to increase dictates a generous interpretation of the space needs. The location of this space will dictate what protocols are used for accessing the space. A small gowning area may be required if this space is located adjacent to but outside of the vivarium. The location may also impact how food is dealt with in the space.

B. Training/Conference

The administrative space should include conference and training space, which can be combined in one room. This space should be large enough for the entire departmental staff to gather in a group, and equipped with appropriate audiovisual and teaching equipment, including a chalk/marker board, a digital projector and video players/recorders. The room should be wired for voice and data connections. This space may also

serve as the departmental library, with storage for hard-copy books as well as non-print media such as videotapes and slide sets. Care should be taken to provide flexible furniture/table systems to facilitate the variety of meeting types that often occur. Sometimes this room is even combined with the break room, but in most cases a separate break room is desirable.

C. Offices

Functions of the modern animal research facility mandate a relatively large administrative workload. The administration of the facility will normally include the director, possibly an associate or assistant director, a business manager, an operations manager, and one or more administrative staff members. All of these individuals need office space, and this space should be in the same area. The office for the operations manager may be located in the animal-care area rather than the administrative area to place this individual closer to his or her daily duties. Office space may also be required for one or more supervisors, one or more clinical veterinarians and one or more veterinary technicians. These offices may be located in or close to animal-care areas. Often, non-vivaria personnel require access to the offices; therefore the location of the offices should be considered carefully. If they are situated in the vivarium, then security protocols must be maintained and protocols set to allow access by visitors and researchers; if outside the vivarium, then protocols need to be developed concerning the movement of vivarium staff into and out of the vivarium, and any gowning procedures that would be required.

D. Information Technology (IT)

Today's administrative functions rely heavily on the use of computers. There is generally a computer or workstation on almost everyone's desk. IT space is required in support of this, and usually consists of one or more closets housing servers, routers and other IT equipment. This equipment should be located such that IT service technicians have access to it without entering the animal facility, other than administrative space. In some instances, this equipment could be located within an interstitial space above the vivarium.

An issue that often comes up is the use of electronic equipment and computers within sterilized areas such as a barrier. Careful protocols should be developed to avoid taking equipment into and out of a barrier from an office area, in order to avoid contamination. Dedicated equipment combined with data links to computers outside the barrier, etc., or a means to decontaminate this equipment should be considered.

E. File Storage

While we live in an electronic age and much information is stored electronically, the animal facility still files a considerable amount of hard-copy records. Storage of these records can be accomplished by allowing room for a sufficient number of file cabinets in the administrative offices, or if there is a large volume of record storage a separate file room would be more appropriate. Consideration should be given to a remote location for long-term storage of material, given the cost of constructing a vivarium.

F. Office Support

Space needs to be provided for other office support equipment, such as copy machines, fax machines and printers. This support equipment is often located in the general office area, but may have a room dedicated to it. A separate dedicated room also often serves to house a communal coffee-maker and/or teapot. Ideally, this room would be a small kitchen with a sink, a refrigerator, storage cabinets and a work counter for the coffee-maker, microwave, etc. Space must also be provided for the storage of expendable office supplies. Usually there is a closet provided for this purpose. Personnel can benefit from an enclosed space for printers, fax machines and copiers in the interest of air quality, noise and hazardous chemicals. This space should be separate from food sources and break spaces.

G. Personnel Health and Hygiene

An area separate from animal housing areas should be provided for personnel to eat, drink and relax during breaks and lunch periods. Generally these areas are equipped with refrigerators and microwave ovens, and sometimes vending machines are situated there. This space should be sufficiently large to accommodate the husbandry staff at peak occupancy.

There must be provisions for personnel toilet, shower and locker facilities. These facilities should be sized based on the maximum number of employees for the facility. While the trend is that more women than men work as animal-care providers, there should be equal provision for males and females. These spaces should be accessible per local codes and the Americans with Disabilities Act, 1991. Space should be available for visitors. Separate lockers, showers and toilets may be required in surgery and other special barrier/containment areas. If these facilities lead directly into the vivarium, then appropriate space for gowning, gown storage and removal will be required. Often a step-over bench is provided to reinforce the protocol of entering a clean environment.

H. Circulation

As the forgoing indicates, modern animal research facilities are very complex and must support the needs of the research staff, the animal-care staff and the animals. Early on, plans should include consideration of movement of all elements

within the facility, including flow cycles for research staff, animal-care staff, maintenance staff, visitors, animals, cages, food, bedding, other supplies and equipment, waste and laundry. Movement of personnel, animals and material into and out of the facility is a critical factor for proper and efficient function of the animal facility (see Chapter 9 in this book).

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Chapter 19

Animal-use Space

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I. INTRODUCTION

Animal-use support space is one of the primary functional areas of an animal research facility. This is separate from but contiguous with the animal housing space, the other primary functional area of the facility. Control of unwanted variables is paramount for research animal facilities because the data obtained from research animals can otherwise be affected, confounding interpretation of research results. In general, animal-use procedures should be conducted in areas separated from the animal-care and housing rooms because, aside from competing with ongoing animal husbandry activities, many use procedures may also affect research animal metabolic, physiologic and behavioral parameters via stimulation of visual, auditory and/or olfactory processes. There are no hard and fast rules regarding the numbers, sizes or types of space that must be included in a facility; these are driven by the anticipated needs that must be accommodated by the institutions' research programs. Different facilities can vary appreciably depending on the programmatic requirements. Typically, the ratio of support space to animal housing space ranges between

30:70 and 70:30, with smaller facilities requiring a proportionally greater amount of space devoted to support (Hessler and Leary, 2002). In order to help define and provide adequate support space it is important to involve a number of people during the planning phase of the facility, including representatives from the veterinary and animal-care staff, the investigative user staff, the IACUC, and the institution's facility engineering, health and safety, and security groups. Depending on the nature of the studies and procedures to be performed, it may be necessary to house animals in very close proximity to the animal-use areas, or even provide housing inside the animal-use areas (e.g., during continuous or prolonged compound administration or sample and data collection, or when hazardous agents are used). It can then be determined whether risk assessment deems containment in a given room is more desirable than transporting animals between separate rooms. Various animal-use support areas are presented in this chapter however, each institution must decide which functions will be required to support its programs.

II. SURGERY

The surgery area provides a support function for the animal-use program, and is utilized for either major or minor procedures with survival or non-survival outcomes. The design of surgical facilities should include consideration for the species to be used, the types of procedures to be performed, the desired throughput or volume of procedures, and the number of people who will work in the suite. Longstanding standards under which surgical procedures are to be performed are provided in the Animal Welfare Regulations (CFR, 1985) and the *Guide for the Care and Use of Laboratory Animals* (the *Guide*; ILAR, 1996). Survival surgical facilities should meet the requirements defined for human surgical suites, which follow the *Guidelines for the Design and Construction of Hospital and Health Care Facilities*, published by the American Institute of Architects Academy of Architecture for Health (AIA, 2001). Hessler (1991) provides an in-depth discussion of considerations for surgery suite design and construction. Survival surgery must be performed aseptically. Proper planning and facility design will greatly aid practices designed to promote asepsis. Hessler and Leary (2002) discuss concepts for aseptic surgical facilities. Major survival surgical procedures on non-rodent mammalian species require surgery facilities designed for aseptic conditions, and may be desirable when high workloads of major-survival rodent surgical procedures are expected. Brown (1994) and Cunliffe-Beamer (1993) provide a comprehensive description of rodent surgical facilities and management. Although dedicated surgical facilities are not required for minor-survival surgical procedures on non-rodent mammalian species, or for surgical procedures performed on rodents, aseptic technique must be used for these activities. The surgical suite should be centrally located relative to the housing areas for larger animal species, the diagnostic and imaging laboratories, the surgical support staff offices, locker and restrooms, and other critical surgical support areas, yet isolated from heavy non-surgery related traffic to minimize the risk of contaminating the surgical suite. This will also provide a more efficient program by minimizing the distances required for animal, personnel, equipment and supply transport. Facility design and management practices should ensure that the high levels of sanitation required for aseptic surgery are always maintained. Controlled access into the surgery suite should be maintained to further minimize unnecessary traffic and therefore help to reduce microbial contamination and post-operative wound infections.

Input from personnel who will perform surgical procedures and provide surgical support is essential in determining the approach and planning of the surgery suite. After determining the range and volume of surgical activities that must be accommodated, it may be discovered that minor procedures can be performed best in a procedure laboratory, or in a dedicated space in an appropriately managed laboratory area. In such instances, the room should be supplied with the appropriate equipment and designed to promote cleaning and disinfection to support aseptic procedures. This would further limit traffic and potential contamination of the surgical suite and operating room.

The surgery suite should accommodate the functional components of aseptic surgery, which include surgical support, animal preparation, surgeons' scrub, operating room and post-operative recovery (ILAR, 1996). The design and location of the operating room is essential to controlling the traffic flow of animals, personnel and materials into the surgery suite. No design is complete without taking into consideration technology, ergonomics and the possibility of future expansion. Figure 19-1 illustrates a surgery suite. Additional areas in the surgery suite include space and provisions for instrument preparation, observation, equipment storage, janitor's closet, imaging equipment, and clean linen. Larger or more dynamic programs with a high volume of survival surgical procedures will require separate rooms for the different activities. Some activities may be combined in defined functional areas in smaller and/or less intensive surgical programs. In such instances a minimum of three support rooms should be provided, consisting of a combined area for pre-operative preparation and post-operative recovery and observation of animals, a separate surgeons' scrub area, and the operating room. Figures 19-2 and 19-3 demonstrate a combined animal preparation/post-operative recovery room and an operating room with an adjacent surgery equipment storage/observation room. Bergdall and Green (2004) describe equipment options for the surgery suite. Preparation and storage of sterile instruments and surgical supplies can be performed in a remote location if properly managed. Staff dressing facilities should be available and, depending on the size of the facility, can be incorporated into the animal facility locker/restroom areas; however, the surgeons' scrub area should be located inside the surgery suite

adjacent to the operating room. Well-planned clustering of the surgery support areas and providing unobstructed access to the operating room from the support areas within the suite will help to minimize contamination. Provision of large viewing windows and a communication system allows for communication and observation while further limiting traffic into the operating room. A well-designed surgical suite will minimize the number of turns for maneuvering, optimize traffic distances between functional areas, limit traffic flow of staff, animals and supplies, and provide adequate space for equipment and supply storage. The sizes of the rooms will be determined by the complexity of the program as well as the intended use of the space. The differential air pressure for the entire suite should be positive, or greater than that in the adjacent areas of the animal facility. The surgery suite is described below.

A. Instrument Preparation and Sterile Supply

The instrument preparation and sterile supply room is used to clean, package, sterilize and store sterile surgical instruments and reusable or disposable sterile supplies such as needles, syringes, catheters, gowns and gloves (Figures 19-2a, 19.2b). This room should be located in close proximity to the scrub area and operating room, and out of the circulation path of other surgical suite support spaces such as imaging, the janitor's closet and equipment storage rooms (Figure 19-1). The functions of this room may be combined with post-operative observation of recovering animals by the veterinary support staff, or the linen laundry room in smaller facilities with less intensive surgery activities.

B. Animal Preparation

Animals are taken to the animal preparation room to be anesthetized, have hair removed (clipped, shaved) and the skin at the surgical site cleaned and disinfected in preparation for surgery (Figures 19-2a, 19-2c). Pre-operative medications and vascular access may be performed in this room, and animals may be held in this room for stabilization and final preparation for surgery. Temporary animal housing space should be provided to accommodate the species that will undergo surgery. Multiple rooms, space for animal holding cages, or several individually ventilated and controlled cubicles may need to be provided, depending on the volume of activities and variety of requirements for each species. Minor procedures such as wound suturing, peripheral vessel cannulation, suture removal, bandage changes, etc., may also be performed in this room. Both pre- and post-operative care services may combined in this area if the volume of procedures and intensity of the surgical procedures is low (Figures 19-1, 19-2a).

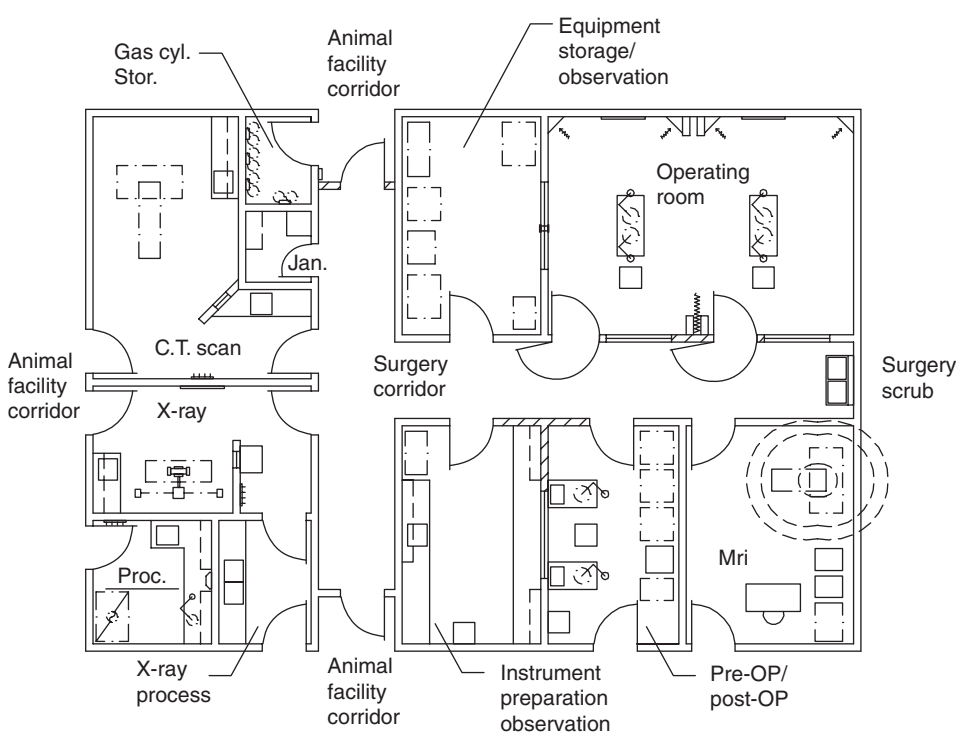


Fig. 19-1 Surgery suite.

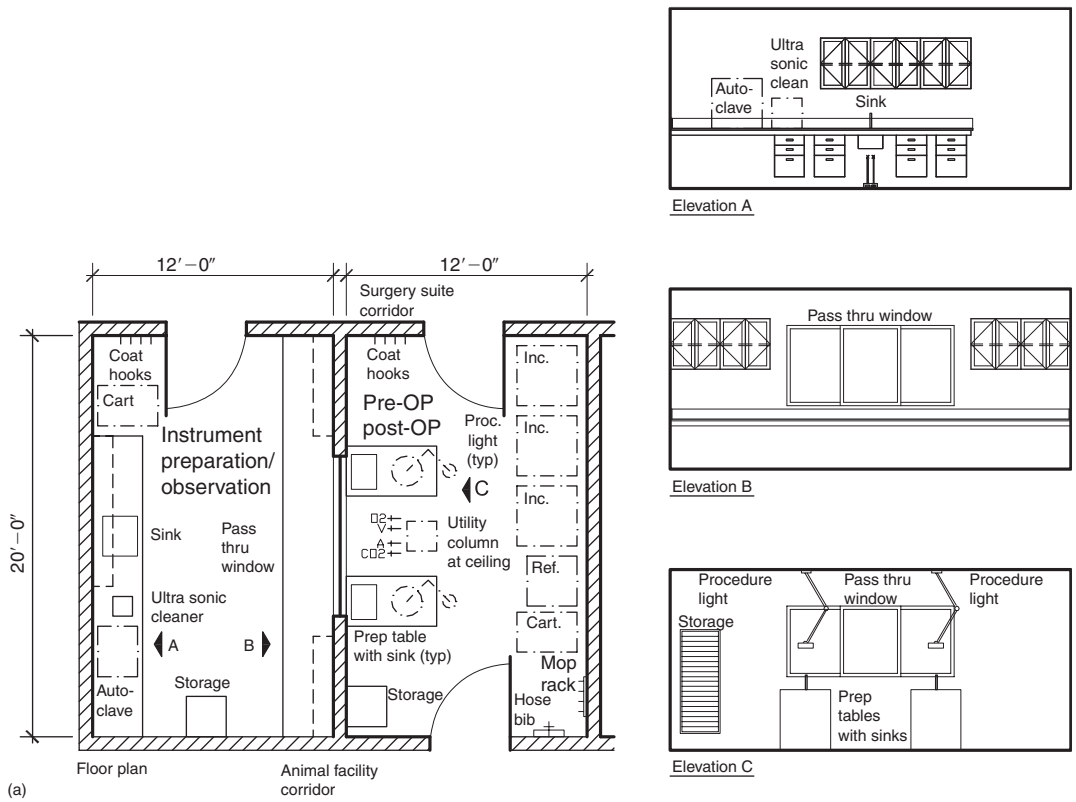


Fig. 19-2 (a) Pre-op/post-op and instrument preparation/observation.

BOX 19-1

FIGURE 19-2A: TEXT SUPPORT

Instrument Preparation and Sterile Supply – Room Needs

Room description: for cleaning surgery instruments, preparation of surgery packs, folding and packaging surgery linens, sterilizing packs, and storing sterile packs and supplies.

Adjacencies: locate adjacent to or as close as possible to the operating room.

Fixed Equipment

Autoclave: a large-chamber steam or gas sterilizer should be located within the vicinity of the surgery suite in smaller facilities, but it may be desirable to locate it within the surgery suite area in larger stand-alone facilities. Due to the sensitivity of some surgical equipment (e.g., fine surgical instruments, endoscopic or fibroscopic lines, reusable telemetry devices, etc.) and to prevent dulling surgical instruments, cold sterilization methods may also be provided. A bench-top autoclave should be provided in the instrument prep and sterile storage room for sterilization of smaller items that may be packaged in this room and utilized in the operating room. Where a large-chamber autoclave is utilized a floor sink adjacent to the autoclave, a stainless-steel exhaust canopy hood to capture steam from the autoclave to alleviate mold growth and adequate clearances for servicing should be provided.

Movable Equipment

Bench-top ultrasonic cleaning unit
Bench-top autoclave.

Work Surfaces and Storage

Work surface: there should be adequate standing height workspace for laying out supplies, instruments and materials in preparation for use in the surgery suite.

Storage: adequate sterile storage space should be provided for various disposable sterile supplies (such as gowns,

BOX 19-1

CONTINUED

gloves and masks) and reusable supplies (such as instruments and equipment) that will be utilized in the operating room and other surgery support areas. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f). They can be assigned to different user groups, stocked with supplies and stored in a designated area of the facility, and relocated into the use space as needed. (Herman Miller, Inc., Zeeland, Michigan).

Animal-Care Needs

This space can be located and utilized to provide observation of animals recovering from surgery by animal care staff.

Accessories

Marker board
Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD)
Coat hooks.

Doors

There should be one 3′8″ min. wide by 7′0″ high door with a view port to the surgery suite.

Windows

None required.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions. Capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sinks should be considered.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Under cabinet task-lighting is required to facilitate and obtain 100 foot-candles at the work surface (ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers if hose wash-down is performed, and be of the GFI type, which allows short-circuiting of the system if it should come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration into the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within research facilities, and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment requiring electrical service is anticipated at perimeter walls.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and will be connected to a file server. Provisions for wireless computer access are becoming more prevalent, and if this is the case in the facility, data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building wide) or in locating individuals within the facility.

(*Continued*)

BOX 19-1

CONTINUED

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 10 changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite spaces should be positive (ASHRAE, 2003).

Animal Preparation – Room Needs

Room description: for support activities for the preparation of animals immediately prior to surgery, including anesthetizing, clipping and shaving.

Adjacencies: conveniently accessible from the animal facility without transporting the animals through the surgery suite. Should be located adjacent to or as close as possible to the operating room to facilitate ease of movement of anesthetized animals into surgery. In smaller programs, this function may be co-located with the post-operative recovery room if desired.

Fixed Equipment

Preparation table: stainless-steel prep table; it is preferable that the table be provided with an integral sink (with hot and cold water) for clipping and cleaning the animal in preparation for surgery. A spray hose at the integral sink facilitates cleaning the animal and the operative site. This table may also be used for anesthetic induction and intubation of the animal prior to moving it to the operating room or performing simple surgery procedures (Suburban Surgical, Inc.).

Ceiling service column: it is advantageous to have a ceiling-mounted service column located above the animal preparation table. A manually operated or motorized service column can be stored out of the way and lowered for use. This column can provide vacuum for scavenging anesthetic gases; gas supply outlets for oxygen, air and nitrous oxide; and general-use electrical outlets (Medical Technologies, Inc., Belmont, CA). If a service column is not provided, then at least one duplex outlet located 84″ above the finished floor should be provided to facilitate cord management while using clippers, etc., during the preparation process.

Movable Equipment

Animal holding cages and/or pens: stainless-steel animal cage racks or larger pens, depending on the species, if the animal is not scheduled to be moved directly from the animal facility and into the operating room after preparation. It is preferable to use bedding mats or pads in lieu of traditional bedding materials such as straw or wood chips.

Animal transport cages or racks: for transporting animals to and from the animal holding facility, along with carts or tables for transporting animals to the operating room.

Gas anesthesia machine(s).

Work Surfaces and Storage

Work surfaces: there should be adequate standing-height workspace for laying out supplies, instruments, equipment and materials to prepare animals for surgery. This can also be achieved with movable carts.

Storage: adequate storage space should be provided for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f). They can be assigned to different user groups, stocked with supplies and stored in a designated area of the facility, and relocated into the use space as needed (Herman Miller, Inc., Zeeland, Michigan).

Animal-Care Needs

Although animals are usually fasted prior to undergoing surgery, this room should have the capability to match the requirements of the balance of the animal holding facility regarding water and feed.

Accessories

Wall clock
Marker board
Cleaning implements holding rack (“mop rack”) (Life Science Products, Inc., Chestertown, MD)
Coat hooks.

Doors

There should be one door each to the animal facility corridor and surgery suite corridor, 3′8″ min. wide by 7′0″ high with a view port in the door to the surgery suite corridor. Controlled access to this room from the animal facility should be considered.

BOX 19-1

CONTINUED

Windows

Observation window from the surgery suite or surgery suite corridor for monitoring progress of preparation of animal for surgery should be provided.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted. The floor should be sloped towards the drain, if provided, which should be centrally located within the room while out of the path of major circulation.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions. Capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: at least two sinks, with hot and cold water, should be provided; one for hand-washing and general cleaning of supplies within the room and a second for animal preparation. Animal preparation sinks should be located adjacent to the animal preparation table or, ideally, be integral to the prep table, with hot and cold water. Hands-free operation of the sinks should be considered.

Hose bib, hose reel and floor drain: the provision of a hose bib with hot and cold water and quick disconnect facilitates cleaning and sanitizing the room. The hose reel should be located adjacent to the hose bib, and provide enough hose length to comfortably wash down the entire room. The hose should also be provided with quick disconnects for the attachment of disinfectant solution containers. The floor drain, if provided, should be equipped with a self-priming valve to ensure that sewer gases are blocked from entering the room.

Gases: air (A), vacuum (V), oxygen (O_2) and carbon dioxide (CO_2) should be provided to the ceiling-mounted service column (if present). Individualized cylinders may be provided within the room for smaller programs, but adequate space must be available and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas, for minimal interruption as the cylinders empty. If a house system is provided, then an adequate number of outlets should be available for each gas required for the anticipated procedures.

Electrical (ASHRAE/IESNA, 2004)

Lighting: fluorescent waterproof fixtures should provide light at 50–70 foot-candles when measured at 3′0″ above the floor. In addition, examination or surgery lights must be provided (Skytron, Grand Rapids, MI), located over the animal preparation table for adequate illumination for surgery preparation and/or to perform minor procedures).

Power: all electrical outlets should have waterproof covers if hose wash-down is performed and be of the GFI type, which allows short-circuiting of the system if it should come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically; and provided with two covers, one for each outlet. This design prevents water penetration into the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within research facilities and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment or cage racks requiring electrical service is anticipated at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

(*Continued*)

BOX 19-1

CONTINUED

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and will be connected to a file server. Provisions for wireless computer access are becoming more prevalent, and if these are provided in the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety, as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 10 changes of 100 percent HEPA-filtered fresh air should be provided. Directional air flow in relationship to the adjoining surgery suite spaces should be negative and positive in relationship to the animal facility (ASHRAE, 2003).

Post-Operative Recovery – Room Needs

Room description: intensive-care unit for the post-operative recovery and special care of the animals.

Adjacencies: conveniently accessible from within the surgery suite. Should be located adjacent to or as close as possible to the operating room to facilitate ease of movement of anesthetized animals and adjacent to observation room, if provided, to facilitate observation of the animal without disturbing them during recovery. In smaller programs this function may be co-located with the animal preparation room, if desired.

Fixed Equipment

Procedure/examination table: stainless-steel construction with an integral sink that is easily cleanable for performing follow-up procedures (Suburban Surgical, Inc.).

Procedure light: located over the animal procedure table to provide adequate lighting to adequately perform support functions (Skytron, Grand Rapids, MI).

Movable Equipment

Animal holding cages and/or pens: Stainless-steel temporary housing arrangements of animal cage racks or larger pens, depending on the species, should be provided for the duration of anticipated stay. Multiple rooms or several individually ventilated and controlled cubicles may need to be provided depending on the variety of requirements for each species. Intensive-care cage units with environmental controls may be necessary to provide and maintain a warm stable environment for recovery. Bedding mats should be used in lieu of traditional bedding materials such as straw or wood chips.

Animal transport cages or racks: for transporting animals back into the animal holding facility.

Carts or tables: for transporting animals to and from the operating room.

Refrigerator: for storage of perishable medications.

Work Surfaces and Storage

Work surface: there should be adequate standing-height workspace for laying out supplies, instruments, equipment and materials for use in the post surgery recovery room.

Storage: adequate storage space should be provided for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f). They can be assigned to different user groups, stocked with supplies and stored in a designated area of the facility, and relocated into the use space as needed (Herman Miller, Inc., Zeeland, Michigan).

Animal-Care Needs

There should be the capability to match the requirements of the balance of the animal holding facility regarding feed and watering.

Accessories

Wall clock
Marker board
Cleaning implements holding rack (“mop rack”) (Life Science Products, Inc., Chestertown, MD)
Coat hooks.

Doors

There should be one each to the animal facility and surgery suite, 3′8″ min. wide by 7′0″ high, with a view port

BOX 19-1

CONTINUED

in the door to the surgery suite. Controlled access to this room from the animal facility should be considered.

Windows

There should be an observation window from the surgery suite or surgery suite corridor for monitoring progress of preparation of animal for surgery, and a large pass-through window to the observation room.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent, and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sink: two sinks, with hot and cold water, should be provided within the room, one for hand-washing and general cleaning of supplies and equipment and a second for uses associated with animal care. Hands-free operation of the sink is recommended at the hand-washing sink, whereas variable temperature control is desirable at the sink associated with animal care.

Hose bib, hose reel and floor drain: the provisions of a hose bib with hot and cold water and a quick disconnect facilitates room sanitation procedures. The hose reel should be located adjacent to the hose bib, and provide enough hose length to comfortably wash down the entire room. The hose should also be provided with quick disconnects for the attachment of disinfectant solution containers. The floor should be sloped towards the drain, which should be located within the room to facilitate room sanitation while out of the path of major circulation. The drain should be equipped with a self-priming valve to ensure that sewer gases are blocked from entering the room.

Gases: there should be provision of one air (A) and one oxygen (O_2) with quick disconnects at each animal recovery pen, cage rack or intensive-care cage unit. Individualized cylinders may be provided within the room for smaller programs, but adequate space must be provided and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas for minimal interruption as the cylinders empty. If a house system is provided, then an adequate number of outlets should be provided of each gas required for the anticipated procedures.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. In addition, examination or surgical lights should be located over the animal preparation table for adequate illumination for surgery preparation and/or to perform minor procedures (ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers if hose wash-down is performed and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration into the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within the research environment and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment or cage racks requiring electrical service are anticipated at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

(*Continued*)

BOX 19-1

CONTINUED

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and will be connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety, as well as a connection to the building paging system, which may be used in times of emergencies (local or building wide) or in locating individuals within the facility.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 10 changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite spaces should be negative (ASHRAE, 2003).

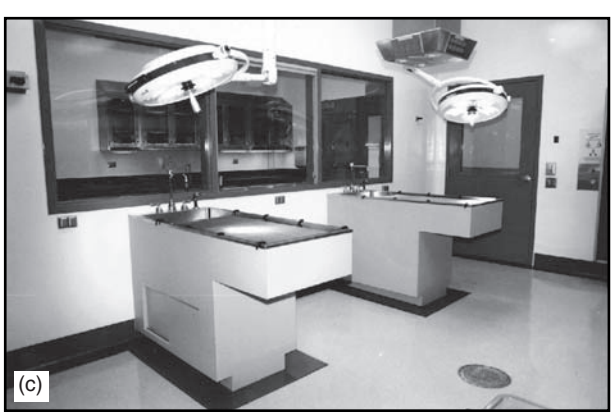


Fig. 19-2 (b) Instrument preparation/observation room. This room has wall-mounted cabinets and standing-height work-counter space with suspended drawers (right-hand side), a portable wall-mounted storage unit (back wall), and a wall-mounted sitting-height work counter with observation windows into the animal prep/post-op recovery room (left-hand side). (c) Animal preparation room. Shown are two preparation tables with integral sinks, ceiling-mounted surgery lights above each preparation table, and a ceiling-mounted utility (electric power, air, vacuum, oxygen and carbon dioxide) service column to facilitate management of electric cords and gas supply lines. (d) Post-op recovery room. This is a different angle of Fig. 19-2(c), showing portions of the two preparation tables (left), surgery lights (above), two portable wall-mounted cabinets (back wall), and an intensive-care cage unit with environmental controls (right wall).

C. Surgeon Preparation

In order to help maintain an aseptic operating room environment, the surgeons' scrub area should be separate from but adjacent to the operating room. There should be provision such that, once scrubbed and prepared for surgery, the surgical team is not required to touch anything that is not sterile. Surgeons must be able to enter the operating room from this area without having to use their hands to move items or open the door into the operating room. Typically this is achieved by provision of a swinging door into the operating room (Figures 19-1, 19-3a, 19-3b).

D. Operating Room

Major or minor surgical procedures with survival or nonsurvival anticipated outcomes will be performed here. Major surgery penetrates or exposes a body cavity or produces substantial impairment of physical or physiologic functions. Minor surgery does not expose a body cavity, and causes little or no physical impairment. Aseptic conditions must be maintained during survival surgical procedures. The primary and secondary sources of surgical wound contamination occur through direct contact and airborne particulates respectively. The infection rate increases as the duration of the procedures increases, as the number of people in the operating room increases, and as the number of air changes in the operating room decreases (Schonholtz, 1976). The level of airborne bacteria in the operating room can be reduced with provision of positive differential air pressure and by limiting the number of people and traffic in the operating room (Fitzgerald, 1979). Ayliffe (1991) and Bartley (1993) describe measures to take for ensuring an adequate supply of high-quality air in the operating room, and recommend concentrating the supply airflow over the operation site rather than over the entire operating room (Ayliffe, 1991). Room-size requirements vary with animal species and with personnel and support equipment needed during the surgical procedures (Hessler, 1991). The number of operating rooms needed to support a surgical program depends on the volume of surgical procedures that must be performed. A larger room with the ability to be subdivided can provide flexibility to the operating room should it be desirable to perform procedures on different animals simultaneously in separate rooms (Figures 19-3a, 19-3c). Such an arrangement would support concurrent procedures, such as multiple training sessions or organ transplant procedures utilizing different animals, or procedures requiring more operating room

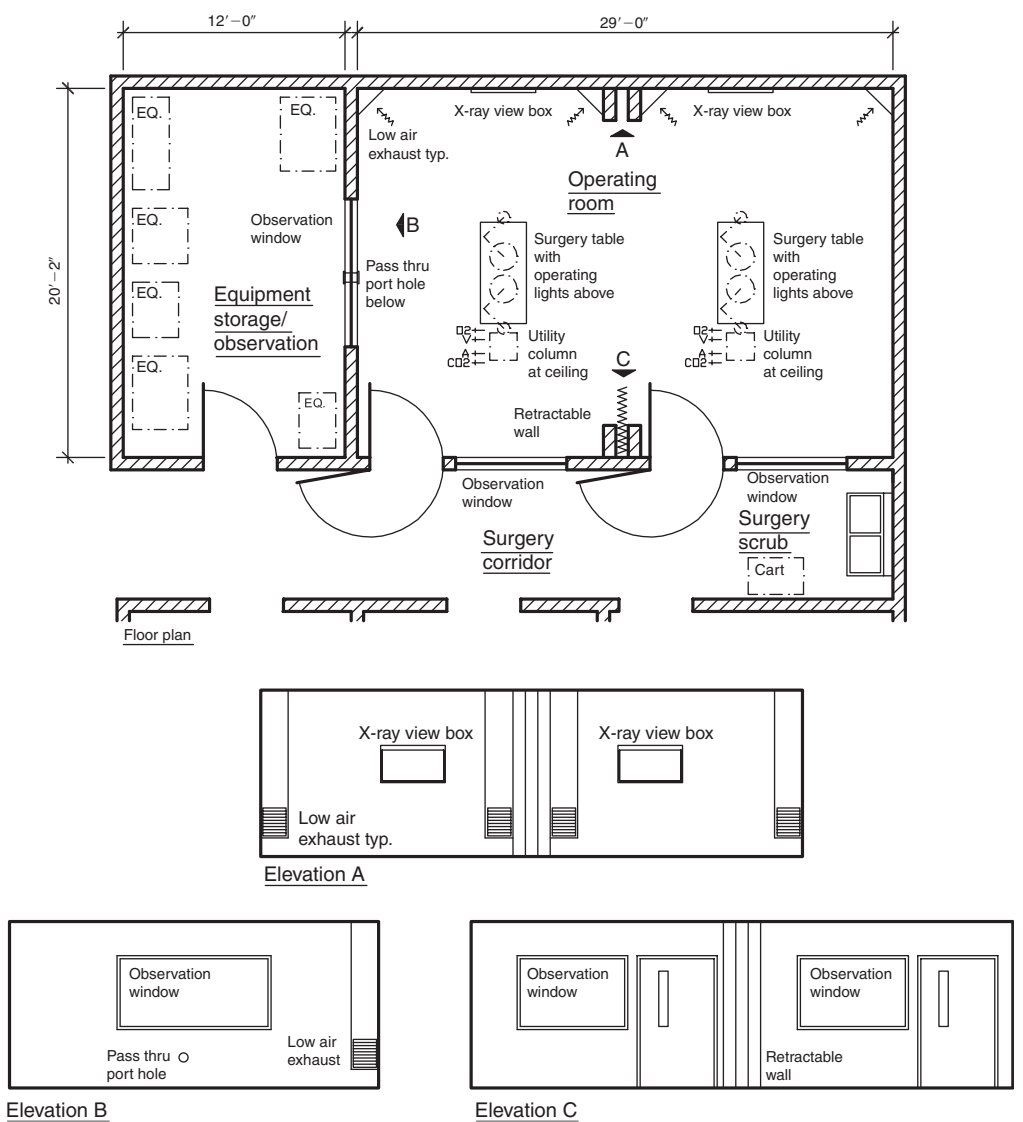


Fig. 19-3 (a) Operating room and equipment storage/observation.

space to be performed while allowing operating room expandability, thereby allowing the potential of more space for procedures requiring more surgical support personnel and equipment. An adjacent equipment room with large viewing windows and a porthole that has removable covers allows data-recording and monitoring lines to run into the operating room. This helps to keep difficult-to-sanitize items (such as research support equipment) outside the operating room (Figures 19-3a, 19-3e). In addition, operating room viewing windows should be provided from the corridor or adjacent observation room for persons not directly involved in the procedures. This will help to control traffic into the operating room, and to maintain an aseptic environment. The operating room should have minimal fixed equipment to facilitate cleaning and maintenance of an aseptic environment (ILAR, 1996).

E. Post-Operative Recovery

Animals are taken to the post-operative recovery room following surgery to provide for adequate post-surgery care and monitoring until sufficient anesthetic and surgical recovery has been achieved to safely relocate them back into their animal housing room. The length of stay may be short, requiring only that the animal recover from anesthesia, or longer if the animals are in need of intensive care and monitoring for more extended stays. A clean, dry environment with provisions for observations and monitoring is necessary. The functions of this room may be combined with the animal preparation procedure room in less intense programs or smaller facilities, and should be located with direct access into the surgery suite corridor and also in close proximity to the animal housing areas (Figures 19-2a, 19-2d). Consideration should be given to the use of cubicles in more intense or high-throughput programs.

F. Other Surgery-Support Functions

1. *Equipment and Supply Storage*

An area to store surgical equipment and non-sterile surgery-suite supplies should be provided. This space may be combined with the surgical observation room for persons who are not directly involved in the procedures, to help control traffic into the operating room (Figures 19-3c, 19-3e). The location of this room within the surgical suite is not crucial, although it should be located out of the circulation path of the animal preparation, the surgeon preparation and the operating room. If this room is located adjacent to the operating room and provided with a pass-through port and viewing windows, it can also serve to hold research monitoring and data-collecting equipment used during some research applications but inappropriate for locating inside the sterile operating room.

BOX 19-2

FIGURE 19-3A: TEXT SUPPORT

Surgery Scrub – Room Needs

Room description: area used by surgeons to scrub prior to gloving and gowning to enter operating room.

Adjacencies: adjacent to operating room in an alcove outside of the operating room or within the instrument prep and sterile supply storage room is adequate.

Movable Equipment

Cart(s) should be provided to hold towels to dry hands and arms after scrubbing and for laying out caps, masks, shoe covers, sterile gowns and surgical gloves.

Accessories

Hands-free aseptic soap dispenser.

Windows

Windows to the operating room are desirable for observation of procedures and activities performed by the surgery staff prior to and during surgery. This space may also be combined with a surgery observation room or area for persons who are not directly involved in the procedures. Observation windows help to control traffic into the operating room and/or surgery suite and to ensure that an aseptic environment in the operating room is maintained.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent, and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and

BOX 19-2

CONTINUED

corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions. Capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Dual or multiple tub surgical scrub sink with hot and cold water and hands-free operation should be provided (Continental Metal Products Co. Inc., Woburn, MA).

Electrical

Lighting: general-purpose lighting is required at a minimum of 70 foot-candles when measured at 3′0″ above the floor (ASHRAE/IESNA, 2004).

Telecommunications

Intercom/paging speakers: connection to the building paging system, which may be used in times of emergencies (local or building wide) or for locating individuals within the facility, should be readily accessible.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 10 changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite spaces should be negative (ASHRAE, 2003).

Operating Room – Room Needs

Room description: used for performing aseptic survival surgery procedures on animals.

Adjacencies: adjacent to surgery scrub area and adjacent to or as close as possible to the pre-operative preparation room, post-operative recovery room and the instrument preparation and sterile supply room.

Fixed Equipment

Ceiling service column: it is advantageous to have a ceiling-mounted service column located above each surgery table to facilitate management of gases and utility service lines (anesthetic carrier gas supply, anesthesia scavenging, electrical) within the operating room. A manually operated or motorized service column can be stored out of the way and lowered for use. The column can provide vacuum for scavenging of gases used during surgery, gas supply outlets for oxygen, air, and nitrous oxide, as well as general use electrical outlets (Medical Technologies, Inc., Belmont, CA).

X-ray view boxes: lighted X-ray view boxes should be available near each surgery table to visualize anatomical images pertinent to the procedure being conducted on the animal.

Retractable wall: if a dividable operating room is desired, then a retractable wall can be provided. This wall must be of a material that is non-porous, waterproof and easily cleanable (Custom Fold Doors, Inc., Burbank, CA). It is not recommended to store the retractable wall within a concealed wall cavity because it would be very difficult to keep clean, resulting in sites that can harbor contaminants.

Movable Equipment

Surgery table: a stainless-steel movable surgery table, which can be easily cleaned, is recommended. The size and type of table is dependent on the types of species. A hydraulic lift table is desirable for use with larger animals (Pro Vet Companies, Loves Park, IL).

There must be adequate space for movable surgical support equipment that is transferred into the operating room to support procedures on an as-needed basis, or that may be connected to the operating room via an umbilical that is passed through a port hole that has a removable cover.

Work Surfaces and Storage

None required or desired. Removable sanitizable wall-mounted supply storage units that contain unique supplies required during the actual procedures may be useful during some procedures (Figure 19-3f). Such storage units would be dedicated to specific investigative groups and to ensure adequate operating room sanitation; these units would be removed from the operating room at the conclusion of the surgery session.

Accessories

Wall clock.

Doors

There should be one 3′8″ min. wide by 7′0″ high door with a view port to each operating room. Door should swing in both directions to facilitate movement into and out of the room.

(*Continued*)

BOX 19-2

CONTINUED

Windows

Observation window should be provided from the surgery scrub area for surgery staff to monitor room preparation for surgery procedure. Viewing windows from the corridor and observation room, if provided, are desirable to allow persons not involved with the surgery procedure to observe the procedures without compromising the aseptic field.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Gases: air (A), vacuum (V), oxygen (O_2) and carbon dioxide (CO_2) should be provided to the ceiling-mounted service column, if present. Individualized cylinders may be provided within the room for smaller programs, but adequate space must be provided, and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas for minimal interruption as the cylinders empty. If a house system is provided, then an adequate number of outlets should be provided of each gas required for the anticipated procedures.

Electrical

Lighting: there should be general-purpose fluorescent room lighting at the perimeter of the surgery table, and one dual-head surgery light (Skytron, Grand Rapids, MI) over each surgery table to provide adequate lighting and eliminate shadows. This light must have substantial support from the structure above to eliminate drift or movement (ASHRAE/IESNA, 2004).

Power: general-use electrical duplex outlets should be provided to the room for movable equipment that will be transported to the room for use during surgery. The location of electrical outlets should be determined after careful consideration of how the room will be used during surgeries to minimize the interference of the equipment or electrical cords during surgery procedures.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and will be connected to a file server. Provisions for wireless computer access are becoming more prevalent, and if these are provided in the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building wide).

Mechanical

HVAC: there should be provision of HEPA-filtered 100 percent fresh air at 20–25 air changes per hour, supplied at the ceiling with a concentration of laminar air flow over the surgery tables rather than over the whole operating room. Low air exhaust should be provided in at least two locations per operating room, near the floor level to reduce airborne particulates. Room temperature should be individually controlled. Differential air flow should be positive in relationship to all adjacent areas (ASHRAE, 2003).

BOX 19-2

CONTINUED

Equipment and Supply Storage – Room Needs

Room description: storage of equipment and bulk supplies utilized in surgery procedures.

Adjacencies: not critical where this space is located within the surgery suite unless utilized to provide support for the operating room via the umbical porthole for hard-to-sanitize items that are required during surgery or as a non-surgical personal observation room. If utilized for surgery support or observation room, it must be adjacent to operating room.

Movable Equipment

Wire shelves: adequate number of stainless-steel wire shelving racks for storage of bulk items.

Gas cylinders may be located in this room, if required, with gases distributed to the operating room or other surgery support spaces.

There must be adequate storage space for movable surgical support equipment that is transferred into the operating room to support procedures on an as needed basis or may be connected to the operating room via an umbilical that is passed through a port with a removable cover.

Storage

Adequate storage space should be provided for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f). They can be assigned to different user groups, stocked with supplies and stored in a designated area of the facility, and relocated into the use space as needed (Herman Miller, Inc., Zeeland, Michigan).

Doors

There should be one 3′8″ min. wide by 7′0″ high door with a view port to the surgery suite. Controlled access to this room should be considered.

Windows

None required, but if this room is combined with observation room functions there should be an observation window into the operating room. Observation windows help to control traffic into the operating room and/or surgery suite and to ensure that an aseptic environment in the operating room is maintained.

Miscellaneous

It is recommended that this room be connected to the operating room via a porthole with a removable cover to allow equipment that is difficult to sanitize to be utilized in the operating room, via umbicals, without compromising the field of surgery.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Electrical

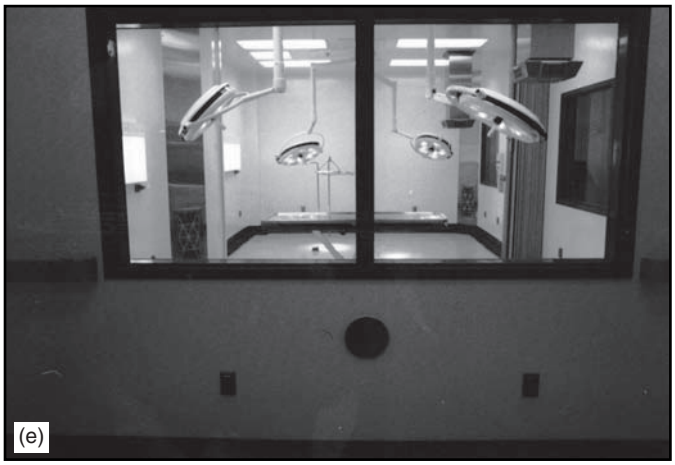
Lighting: general lighting levels for storage must be provided – a minimum of 50–70 foot-candles when measured at 3′0″ above the floor (ASHRAE/IESNA, 2004).

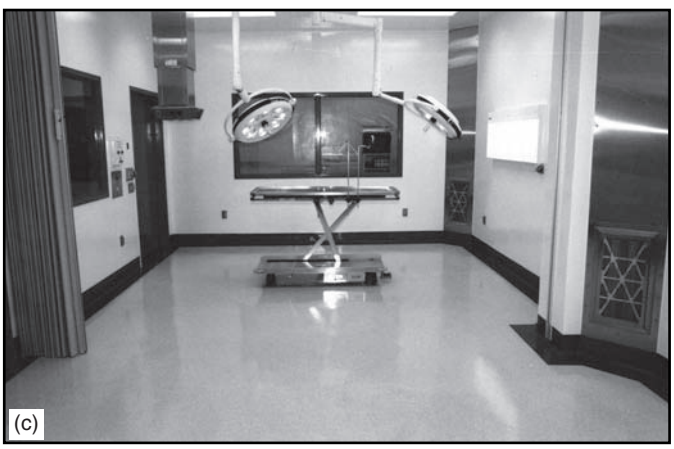
Power: general-purpose duplex outlets must be provided, with additional outlets for equipment specific needs – for example, for equipment that may need to be recharged.

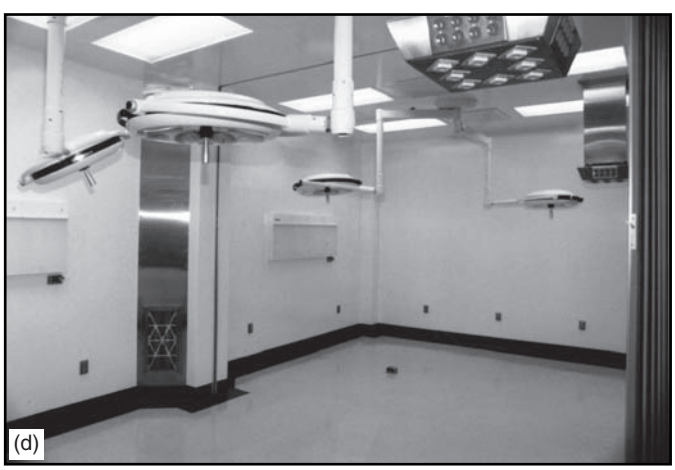
Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least six changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite spaces should be negative (ASHRAE, 2003).







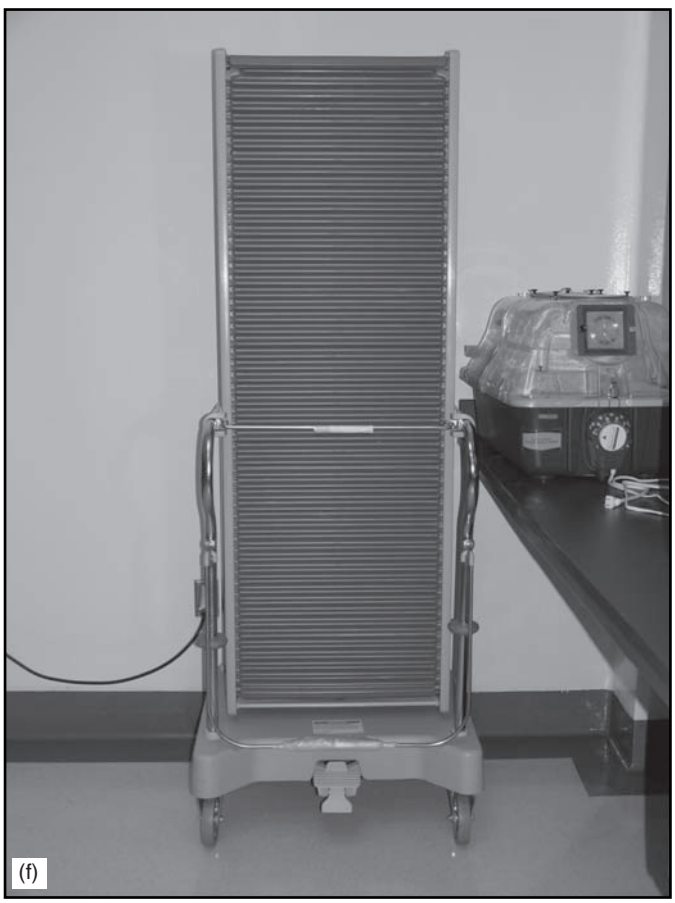


Fig. 19-3 (b) Surgeons' scrub area. A dual hands-free surgical scrub sink with soap dispenser is located against the back wall. Two doors and two observation windows into the OR (left) and a door to the animal preparation/post-operative recovery area (right) are shown. (c) Operating room (OR). Shown is a double-sized OR with a retractable wall to divide the OR space as needed. An X-Ray view box and two low air returns (right wall), dual arm ceiling-mounted surgery lights, a retractable ceiling-mounted utility supply column (left), a movable surgery table (center) and a large observation window into an equipment storage room (center back wall) are shown. (d) Operating room (OR). This a different angle of Figure 19-3(b), showing two X-ray view boxes (left wall), two sets of dual arm ceiling-mounted surgery lights and two retractable ceiling-mounted utility supply columns (right). (e) Equipment and supply storage room with observation window into the OR. Note the porthole (lower center) with a removable cover to allow equipment that is difficult to sanitize to be utilized in the operating room, via umbilicals, without compromising the field of surgery. (f) Portable wall-mounted storage cabinet with transport lift cart in place. These lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient. They can be assigned to different user groups, stocked with supplies and stored in a designated area of the facility, and relocated into the use space as needed.

2. *Locker/Changing Room*

The locker/changing room is where surgery personnel change into surgical attire. One male and one female locker/changing/shower room should be provided. In smaller programs, shared unisex facilities may be provided if equipped with interlocking doors for privacy. Location within the surgery suite is preferable, but a location that has convenient and direct access into the surgery suite is acceptable. Access from the animal facility corridor, which then has access directly into the surgery suite, is preferred when this area is dedicated to the surgery suite. In smaller programs where other animal facility personnel also utilize this area, it is recommended that it be located as close as possible to the surgery suite with convenient access from the locker/changing room into the surgery suite, and also so as to minimize traffic between the animal holding areas and the surgery suite. One full-height locker per person should be provided to allow for changing from street clothes into surgical attire. One half-height locker per person is adequate if staff are not required to change out of their outer garments. A fixed or movable sitting bench, hampers for soiled laundry, and storage for different-sized surgical scrubs (e.g., a hanging clothes rack or wire shelves for clean surgical attire) should be provided. At least one toilet compartment, sink and shower (if provided) for each sex must be disabled-accessible as per the Americans with Disabilities Act (CFR, 1994). Electrical power should be provided for general use (e.g., hair dryers, cleaning, service, etc.). Toilet and shower areas should have a minimum of 10 total air changes per hour (AIA, 2001) with 100 percent general exhaust. There should be adequate heating and cooling supply air to provide a comfortable environment.

3. *Laundry/Linens*

The laundry/linen room is used for cleaning reusable gowns, scrubs and linen utilized in the surgery suite. Alternatively, a commercial laundry service can be used; however, an area for storage of surgery suite garments should be available. An adequate work surface must be provided for sorting of soiled linens and folding of clean linens. There should be a sink with hot and cold water, a wall-mounted hot and cold water supply valve and drain for the clothes washer, a dedicated exhaust duct for the dryer, and a floor drain equipped with a self-priming valve to ensure that sewer gases are blocked from entering the room. This room could also house a large autoclave for sterilizing surgery garb and supplies. The location of this room within the surgical suite is not crucial, but, if included, it should be located out of the circulation path of the animal preparation, surgeon preparation and operating room. Directional airflow should be negative in relationship to the adjoining spaces.

4. *Janitor's Closet*

The surgery suite janitor's closet provides storage of detergents, disinfectants and equipment utilized for general cleaning of the surgery suite (Figure 19-1). The location of this room within the surgery suite is not crucial, although, if included, it should be located out of the circulation path of the animal preparation, surgeon preparation and operating room. A service sink with hot and cold water and service sink hose-bib type faucets should be provided. Floor-mounted service sinks allow easy access for dumping mop buckets. Hose-bib type faucets allow for buckets to be filled without lifting. A floor drain should be provided, equipped with a self-priming valve to ensure that sewer gases are blocked from entering the room, along with general-purpose illumination, supply and exhaust air, and one moisture-resistant duplex electrical outlet.

5. *Compressed Gas Cylinder Storage*

A gas cylinder storage room is utilized for the bulk storage and source for building-wide distribution of gases such as oxygen, nitrous oxide and carbon dioxide. Gases can be distributed into the surgery suite and other areas of use, such as procedure laboratories. Provision of a dedicated location for gas cylinder storage helps facilitate sanitation and minimizes clutter in the various animal-use areas that require gas services. Typically, a commercial vendor provides compressed gases that are stored in a warehouse until the cylinders are delivered to the facility. Normally, warehouses are not maintained under the sanitary conditions required for research animal facilities, and therefore, unless protocols are developed to sanitize the cylinders prior to movement into the facility, the cylinders can compromise the sanitary conditions that should be maintained in most areas of an animal facility.

The addition of a gas manifold (Figure 19-4a) allows serial connection of multiple cylinders and audible and/or visual enunciation (Figure 19-4b) when the available gas in the cylinders reaches levels that could interrupt the gas distribution and prevent continuous gas delivery. Manifolds can be obtained that provide either manual or automatic switching between empty and full cylinders to maintain the continuous flow of gases (e.g., Linde Gas LLC, Independence, Ohio; http://us.lindegas.com).

The gas cylinder storage room should be in a convenient location outside of the surgery suite that is easily accessible by delivery personnel (Figure 19-1). The alarm should be located in an area of high traffic and visibility, to alert personnel when a gas supply cylinder has been depleted and the manifold needs to be switched to obtain gas from a full cylinder or cylinder replacement is necessary.

III. DIAGNOSTIC LABORATORIES

Depending on the size and complexity of the research animal program, some or all diagnostic services may be provided by outside commercial laboratories or by an in-house laboratory. Typically, specimen samples collected in other areas of the animal facility are delivered to the diagnostic laboratory for analysis.

Fig. 19-4 (a) Gas cylinder storage. This automatic gas cylinder storage room is utilized for the bulk storage and source for building wide distribution of gasses (oxygen, nitrous oxide and carbon dioxide). These automatic switching gas manifolds allow serial connection of multiple gas cylinders to ensure that gas distribution is not interrupted.

Fig. 19-4 (b) Entrance to gas cylinder storage room. This room is conveniently located outside of the surgery suite and easily accessible by delivery personnel. The alarm adjacent to the door is located in an area of high traffic and visibility, to alert personnel when a gas supply cylinder has been depleted and the manifold needs to be switched to obtain gas from a full cylinder or cylinder replacement is necessary.

Diagnostic laboratory services support the program of disease surveillance, diagnosis, treatment and control; support quality assurance evaluations for sanitation and sterilization processes; and may also be used to support various research activities. The diagnostic services augment gross pathology (necropsy), histopathology, clinical pathology, microbiology, hematology, clinical chemistry and serology (ILAR, 1996). The requirement, size and need for a diagnostic laboratory varies depending on the institution's program needs. The types, number and complexity of diagnostic procedures needed, and whether or not it is feasible to obtain commercial diagnostic services, are factors to consider when deciding on the establishment of in-house diagnostic services. Additional consideration should be given to the institution's ability to utilize standardized testing methodologies, which provide credibility and consistency to analyses. In some situations it may be more efficacious to resort to commercial laboratories that are set up for these purposes. In-house laboratory procedure space that is sufficient for processing specimen samples for delivery to a comprehensive diagnostic laboratory may be adequate for less complex animal programs (Hessler and Leary, 2002). Conversely, in-house high-volume comprehensive diagnostic laboratories may require multiple rooms or spaces (Figures 19-6, 19-7 below), which additionally requires special equipment, reagents, test kits, etc. Due to varying programmatic requirements, each institution must determine the extent of diagnostic services needed; however, fundamental capabilities should be provided in all facilities (Figure 19-5a). Smaller institutions may perform minor tasks in procedure laboratories when the diagnostic procedures are relatively straightforward and the throughput is low, but it may be more efficacious to provide a designated diagnostic laboratory inside the animal facility for larger and more complex laboratory animal programs (Simmons, 1991). Provision of a multi-task space would allow for analysis of sample specimens collected in other areas of the animal facility. However, some diagnostic procedures may be incompatible, and care should be taken to provide separate rooms or workstations as required.

Design considerations for diagnostic laboratories are similar to those for research laboratories and necropsy areas, and these functions are often interdependent. A location adjacent to the administrative/training area is desirable for the diagnostic laboratory (Hessler and Leary, 2002). Specimen samples delivered to this lab are collected in various support areas located inside or outside the animal facility. Access into the diagnostic laboratory should be convenient for personnel, and should also facilitate specimen delivery and shipping. Workspaces should be designed to facilitate cleanliness and minimize contamination of specimens.

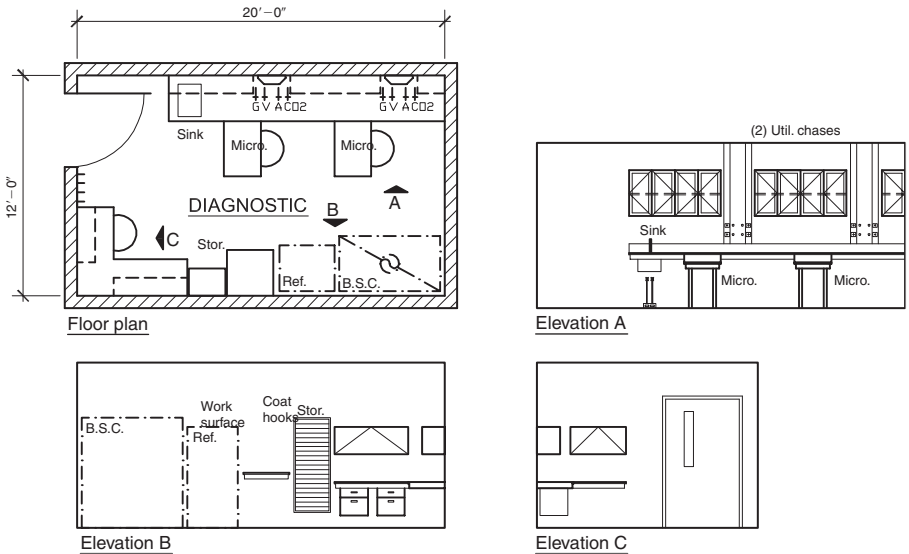


Fig. 19-5 (a) Diagnostic laboratory.

BOX 19-3

FIGURE 19-5A: TEXT SUPPORT

Diagnostic Laboratories – Room Needs

Room description: used as diagnostic laboratory support and specimen analysis for animal facility protocol and research.

Adjacencies: location not critical within the facility. Adjacent to necropsy is preferable in larger programs, or with convenient access to necropsy in smaller programs.

Fixed Equipment

Hazardous fume collection: a back-draft table, Type II or III Biosafety Cabinet, fume hood or canopy hood to scavenge hazardous fumes utilized during the euthanasia and tissue specimen fixation processes. Back-draft tables may provide the most flexibility and convenience during procedures, whereas biosafety cabinets or fume hoods can make it awkward or difficult to perform some activities.

Movable Equipment

Refrigerator: adequate refrigeration must be provided for various supplies (e.g., media, agents and text kits).

Microscope table: there should be vibration-free work tables for use with sensitive equipment or microscopes as required (Kinetic Systems, Inc., Boston, MA).

Work Surfaces and Storage

Work surface: there must be adequate standing-height workspace for laying out supplies, instruments, equipment and materials for use in the diagnostic laboratory, and adequate sitting-height workspace for recording data and microscope use.

Storage: adequate storage space should be provided for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f) (Herman Miller, Inc., Zeeland, Michigan).

Accessories

Marker board

Cleaning implements holding rack (“mop rack”) (Life Science Products, Inc., Chestertown, MD)

Peg board (Inter Dyne Systems, Inc.)

Coat hooks.

Doors

There should be one 3′8″ min. wide by 7′0″ high door with a view port into the animal holding facility. Controlled access to this room from the animal facility should be considered.

Windows

None required unless located adjacent to necropsy, in which case a pass-through window can be useful.

(*Continued*)

BOX 19-3

CONTINUED

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sinks should be considered.

Gases: provision of air (A), vacuum (V), oxygen (O_2) and carbon dioxide (CO_2) to the surface-mounted utility chases. Individualized cylinders may be provided within the room for smaller programs, but adequate space must be provided and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas for minimal interruption as the cylinders empty. If a house system is provided, then an adequate number of outlets should be provided of each gas required for the anticipated procedures.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Under-cabinet task lighting is required to facilitate and obtain 100 foot-candles at the work surface (ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration to the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within a lab and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of bench top work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment will be located at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and will be connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least six changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining spaces should be negative (ASHRAE, 2003).

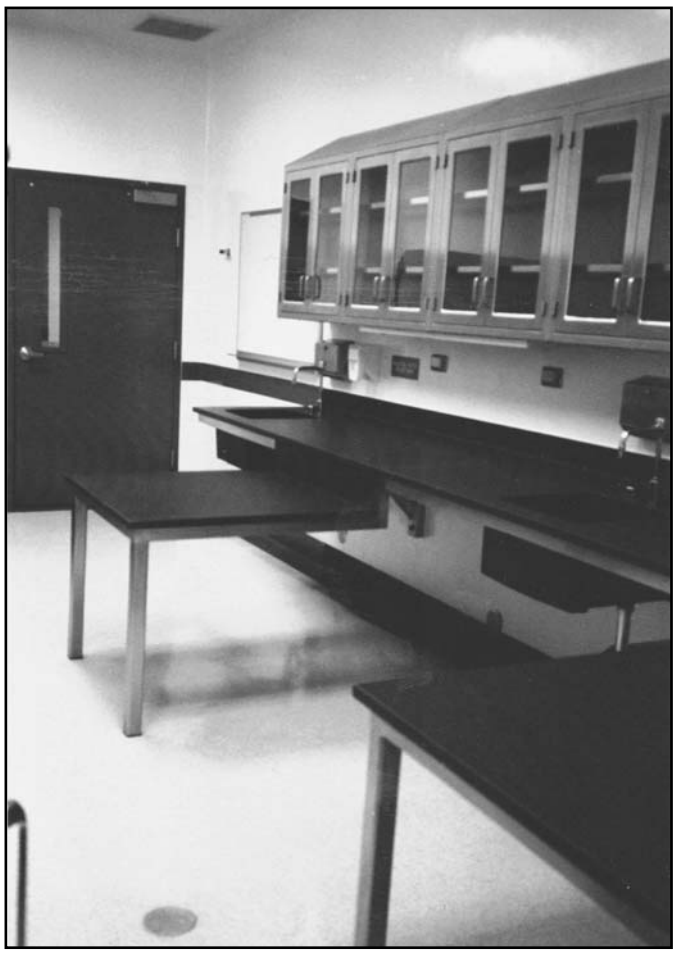


Fig. 19-5 (b) Diagnostic laboratory. Upper stainless steel cabinetry, wall-mounted work-counter space, and two-microscope counter surfaces are shown. Note that none of the casework extends to the finished floor, which facilitates cleaning. (c) Diagnostic laboratory. This is Figure 19-5(b) from a different angle.

IV. EUTHANASIA

In many instances, euthanasia is performed in the necropsy area or in one of the other animal-use support areas where end-of-study or terminal procedures are performed. However, in some situations (e.g., high-volume programs, preclinical development activities involving toxicology and pharmacology procedures, etc.) it might be desirable to provide a designated area or room for this purpose in which space for a euthanasia chamber and other associated equipment and supplies is available. This room should be sized and equipped to accommodate the anticipated volume of activities for the animal species to be used and their transport cages. It is not uncommon for teams of up to a dozen or more prosectors to work together in the necropsy area during end-of-study specimen collection and processing. In such instances, an area for euthanasia immediately adjacent to the necropsy room, and with easy access into necropsy for transferring animal carcasses, can be beneficial to the smooth and safe flow of activities while still allowing some degree of separation during high-volume activities (i.e., it minimizes congestion, animal anxiety, and potential errors). Moral and ethical concerns require that humane practices be observed when animals are euthanized. Euthanasia techniques should result in rapid loss of consciousness followed by death, and should minimize animal distress, including fear, anxiety and apprehension prior to loss of consciousness (AVMA, 2001). The room used for euthanasia should have limited visibility from outside areas and should be designed to facilitate easy sanitation, with good ventilation and 100 percent air exhaust to minimize residual odors resulting from previous euthanasia activities.

V. NECROPSY

The necropsy room is utilized for veterinary diagnostic purposes, and also for collection of experimental tissue specimens, implanted biodevices and experimental data (Figures 19-8, 19-9). Assessment of information collected from sentinel animals housed within animal holding rooms and colony animals that die unexpectedly may reveal disease

processes, experimental conditions or environmental parameters that adversely impact animal health or research results. End-of-study analysis of tissues collected and retrieval of experimental biodevices from research animals also provides useful information to investigators. Due to the use or presence of hazardous agents such as chemicals (e.g., tissue fixatives, chemotherapeutic, toxic and carcinogenic chemicals) and contagious or infectious biological agents (bacterial, fungal, parasitic, viral), this room can be one of the highest safety risks to both humans and animals in the facility. Additionally, the necropsy room should be designed to meet the standards of a human autopsy room (AIA, 2001) and located in a relatively remote or isolated area physically separated from animal housing areas and away from general circulation within the facility. Ideally, it should be located near or adjacent to the area for carcass collection, with convenient access to the facility exterior where refuse is removed from site for incineration or final disposal. It is desirable to locate the necropsy area near the diagnostic laboratory but as far away from the traffic flow into survival surgery areas as physically possible. Simmons (1991) provides a discussion of considerations for necropsy design and construction. Figures 19-5, 19-8 and 19-9 illustrate a necropsy room with an adjacent histopathology/diagnostic laboratory, an enlargement of the necropsy room, and a smaller necropsy room (for lower volume programs), respectively.

Due to the hazardous nature of the chemicals and infectious biological agents that may be present, good exhaust is imperative. This can be accomplished by filtering all air removed from the room by either HEPA filtration or the use of Type II or III biosafety cabinets. The necropsy table as well as the chamber or area used for animal euthanasia requires specific attention, where dedicated exhaust with adequate airflow is provided to ensure that hazardous fumes and particulates are removed. In addition, differential air pressure in the necropsy room should be negative to adjacent areas of the facility to contain potential aerosolized contaminants or hazardous vapors and chemicals within the room.

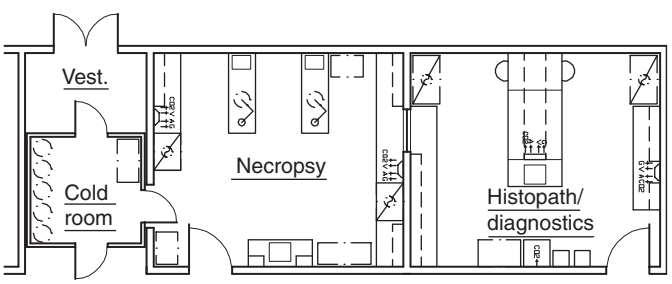


Fig. 19-6 Histopathology/diagnostic laboratory suite.

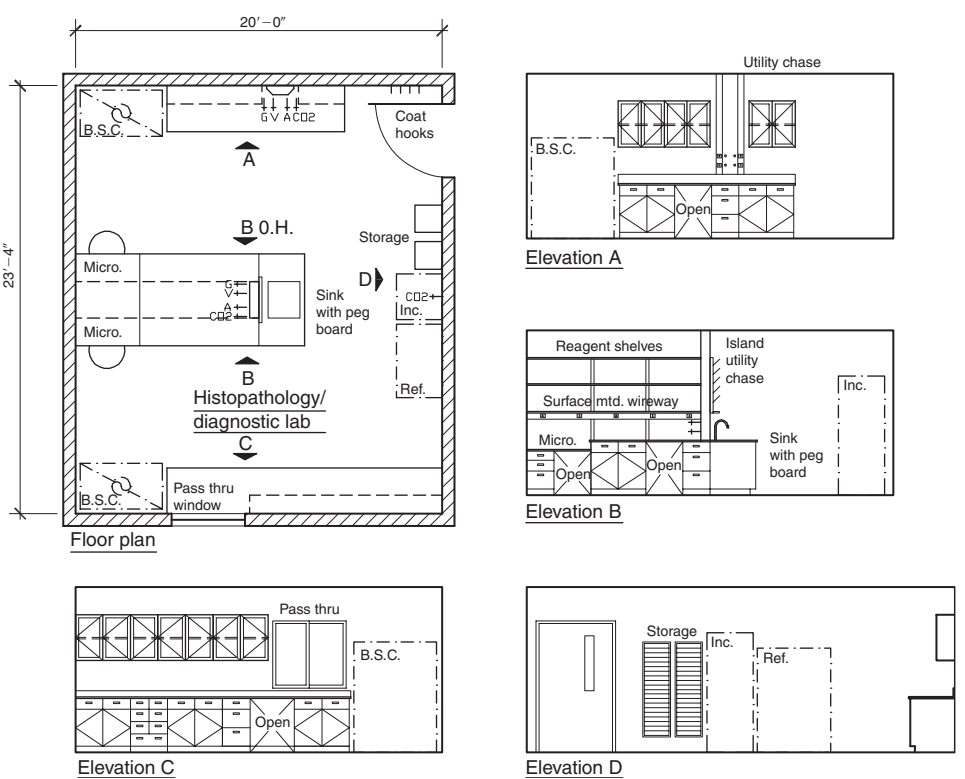


Fig. 19-7 Histopathology/diagnostic laboratory.

BOX 19-4

FIGURE 19-7: TEXT SUPPORT

Histopathology/Diagnostic Laboratory – Room Needs

Room description: used as diagnostic laboratory support and specimen analysis for animal facility protocol and research.

Adjacencies: location not critical within the facility. Adjacent to necropsy is preferable in larger programs, or with convenient access to necropsy in smaller programs.

Fixed Equipment

Hazardous fume collection: a back-draft table, Type II or III Biosafety Cabinet, fume hood or canopy hood to scavenge hazardous fumes utilized during the euthanasia and tissue specimen fixation processes. Back-draft tables may provide the most flexibility and convenience during procedures, whereas biosafety cabinets or fume hoods can make it awkward or difficult to perform some activities.

Movable Equipment

Refrigerator: adequate refrigeration must be provided for various supplies (e.g. media, agents and text kits).

Microscope table: there must be vibration-free work tables for use with sensitive equipment or microscopes as required (Kinetic Systems, Inc., Boston, MA).

Work Surfaces and Storage

Work surface: there must be adequate standing-height workspace for laying out supplies, instruments, equipment and materials for use in the diagnostic laboratory, and adequate sitting-height workspace for recording data and microscope use.

Storage: adequate storage space should be provided for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f) (Herman Miller, Inc., Zeeland, Michigan).

Accessories

Marker board

Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD)

Peg board (Inter Dyne Systems, Inc.)

Coat hooks.

Doors

There should be one 3′8″ min. wide by 7′0″ high door with a view port in the door to the animal holding facility. Controlled access to this room from the animal facility should be considered.

Windows

None required unless located adjacent to necropsy, in which case a pass-through window can be useful.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sinks should be considered.

Gases: provision of air (A), vacuum (V), oxygen (O_2) and carbon dioxide (CO_2) to the surface-mounted utility chases. Individualized cylinders may be provided within the room for smaller programs, but adequate space must be provided and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas for minimal interruption as the cylinders empty. If a house system is provided, then an adequate number of outlets should be provided of each gas required for the anticipated procedures.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Under-cabinet task lighting is

(*Continued*)

BOX 19-4

CONTINUED

required to facilitate and obtain 100 foot-candles at the work surface (ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration to the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within a lab and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of bench top work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment will be located at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and will be connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent and if provided by the facility, data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least six changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining spaces should be negative (ASHRAE, 2003).

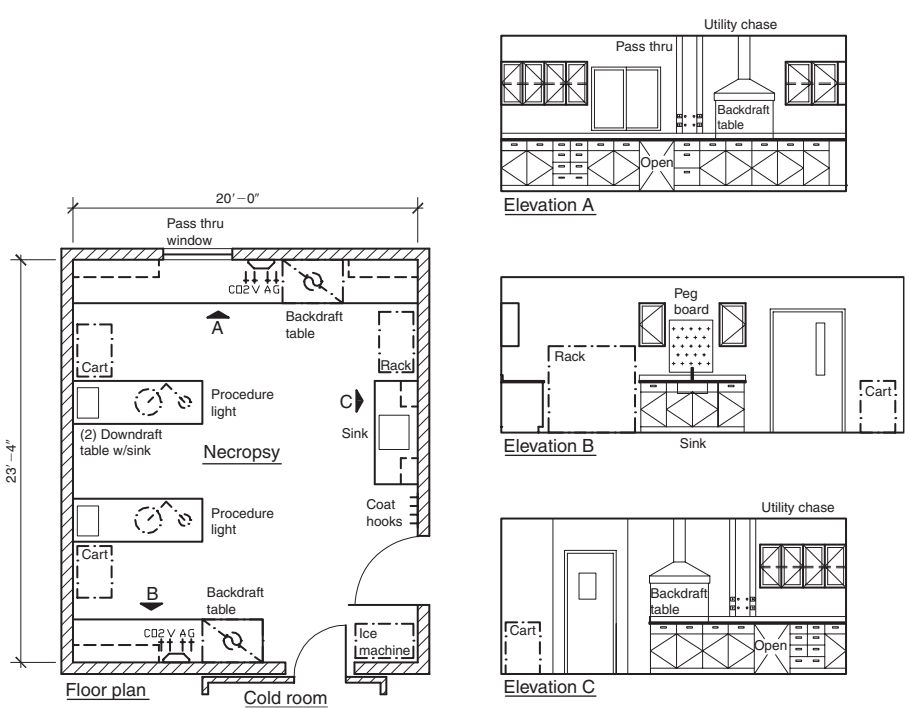


Fig. 19-8 Necropsy room (double).

BOX 19-5

FIGURE 19-8: TEXT SUPPORT

Necropsy – Room Needs

Room description: personnel utilize this space for collecting data and tissue specimens, compiling the associated documents, and utilizing supplies instruments, equipment and materials for collecting tissues and biodevices.

Adjacencies: location is not critical within the facility. Adjacent to the histopathology/diagnostic laboratory is preferable in larger programs, or with convenient access to the diagnostic laboratory in smaller programs. When the necropsy room throughput warrants a walk-in refrigerator and/or freezer, it is advisable that those who are not performing procedures inside the necropsy room not enter the necropsy room itself. This can be accomplished by having dual access into each space. By providing a second door to the refrigerator from the animal holding facility corridor side of the facility, allowing access for those who are placing animals to be necropsied into the refrigerator, and a second door accessible to those who are picking up the carcasses to be incinerated, access to the necropsy room can be regulated. Ideally, the secondary access door would be located adjacent to the refuse pick-up area. To ensure controlled access to the necropsy room and facility by unauthorized persons, the door from the freezer into the necropsy room should be designed as a controlled entry.

Fixed Equipment

Necropsy table: a stainless-steel down-draft table with the work surface sloped towards an integral sink with built-in garbage disposal is most desirable. Air should be captured at a minimum of 12″ above the work surface.

Hazardous fume collection: a back-draft table, Type II or III Biosafety Cabinet, fume hood or canopy hood to scavenge hazardous fumes utilized during the euthanasia and tissue specimen fixation processes. Back-draft tables may provide the most flexibility and convenience during procedures whereas biosafety cabinets or fume hoods can make it awkward or difficult to perform some activities.

Ice machine: access to flaked ice is necessary for preservation of biological specimens. If provided within the room, a floor sink will be required adjacent to the icemaker for water generated by the unit, which is discharged via the condensate line.

Movable Equipment

Refrigerator/freezer: this should be located within the necropsy room and dedicated to carcass storage. Space requirements for storage capacity are dictated by the size of the program. Smaller facilities may find a combination refrigerator/freezer adequate to contain the number of carcasses that are in storage waiting for diagnostic studies or waiting to be picked up for incineration. In addition, in smaller programs a supplemental freezer may be located in a remote area near the refuse pick-up area for bulk supply of carcasses. Larger programs' storage requirements may warrant providing a walk-in refrigerator unit.

Animal transport cages or racks: for transporting animals from the animal holding facility should be available.

Work Surfaces and Storage

Work surface: there should be adequate standing-height workspace for laying out supplies, instruments, equipment and materials for use in the necropsy room. The number of standing-height workspaces will be driven by the desired number of people (e.g., number of investigators, veterinarians and technicians) to be simultaneously accommodated in the room. For instance, a high-volume diagnostic necropsy laboratory or a toxicology necropsy area with several prosectors would require much more space than is needed for a relatively small animal program. In addition, an adequate number of kneehole spaces should be provided for the performance of work best accomplished while sitting down, such as when labeling numerous sampling containers, recording data or using microscopes.

Carts or tables: provision as needed, as supplemental work surfaces while working at the necropsy tables.

Storage: adequate storage space should be provided for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f)(Herman Miller, Inc., Zeeland, Michigan).

Accessories

Marker board

Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD)

Peg board (Inter Dyne Systems, Inc.)

Coat hooks.

(*Continued*)

BOX 19-5

CONTINUED

Doors

There should be one 3′8″ min. wide by 7′0″ high door with a view port. Controlled access to this room from the animal facility should be considered.

Windows

None required unless located adjacent to the histopathology/diagnostic laboratory, in which case a pass-through window can be useful.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: at least two sinks, with hot and cold water, should be provided, one with a garbage disposal unit for preparation of carcasses and performing the necropsy procedures; this need may be met if utilizing a necropsy table with an integral sink and garbage disposal. The second sink is utilized for general cleaning and sanitation purposes in the necropsy room. Although the use of one sink may be acceptable, adequate procedures should be developed to minimize or avoid cross-contamination of other room supplies with debris from animal carcasses. If only one sink is provided, it should be equipped with a garbage disposal.

Hose bib, hose reel and floor drain: the provision of a high-pressure hose bib with a temperature gauge and quick-disconnect and hose reel facilitates the removal of gross debris prior to sanitizing. The hose reel should be located adjacent to the hose bib and provide enough hose length to comfortably wash down the entire room. The hose should also be provided with quick disconnects for the attachment of disinfectant solution containers. The floor should be sloped towards the drain, which should be centrally located within the room while out of the path of major circulation. The drain should be equipped with a self-priming valve to ensure that sewer gases are blocked from entering the room.

Gases: provision of air (A), vacuum (V), oxygen (O_2) and carbon dioxide (CO_2) to the surface-mounted utility chases. Individualized cylinders may be provided within the room for smaller programs, but adequate space must be provided and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas for minimal interruption as the cylinders empty. If a house system is provided, then an adequate number of outlets should be provided for each gas required for the anticipated procedures.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Under-cabinet task lighting is required to facilitate and obtain 100 foot-candles at the work surface. Procedure light should be provided at the ceiling over down-draft tables to eliminate shadows (Skytron, Grand Rapids, MI; ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration to the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within a lab and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of bench top work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment will be located at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely

BOX 19-5

CONTINUED

interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room that will be connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system which may be used in times of building-wide emergency or for locating individuals within the facility.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 12 changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining spaces should be negative (ASHRAE, 2003).

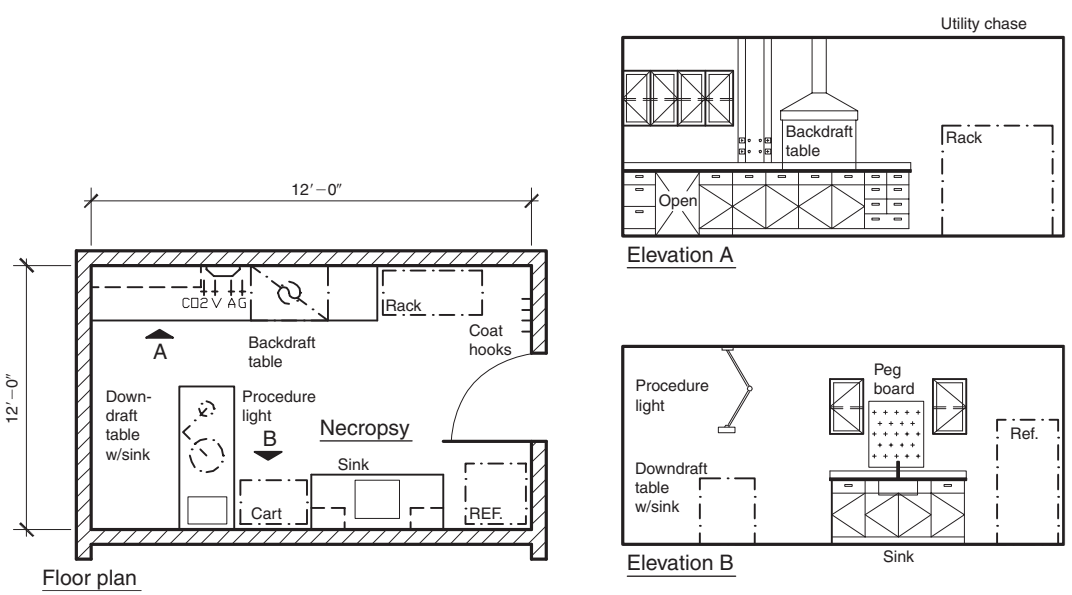


Fig. 19-9 Necropsy room (single).

VI. ANIMAL PROCEDURE LABORATORIES

The concept of and need for providing animal procedure laboratories inside the animal facility has evolved over the years. Earlier practices, whereby either animal-use procedures were performed inside the animal holding rooms or animals were transported between the animal housing facility and research laboratories, impeded sound animal and human health and safety standards, and also introduced variables that could confound interpretation of research data. Experience has shown that animal welfare and study results might be compromised when invasive procedures are performed inside animal holding rooms. This is also true when animals are transported back and forth between the animal housing facility and research laboratories. Additionally, the simultaneous activities of the animal-care personnel and the animal-use personnel can often conflict when procedures are carried out in the animal housing rooms. Alternatively, some less invasive procedures, such as observational and behavioral procedures, may be facilitated when performed inside the animal holding room environment;

however, as a general rule, animal-use procedures should not be performed inside animal holding rooms. Contamination control is impeded when supplies and equipment required for animal-use procedures are stored inside animal holding rooms. While investigator maintained laboratories might be equipped with specialized equipment required for animal use, the transfer of animals back and forth between the animal housing facilities and the research laboratories has drawbacks and is discouraged. Therefore, provision of adequate dedicated animal-use procedure laboratories within the research animal facility is desirable for minimizing occupational health and safety concerns, security and biosecurity concerns, and environmental variables that may confound animal-study results, and is recommended; performing animal-use procedures inside the animal housing rooms, or the transport of animals between research laboratories and the animal facility, is strongly discouraged. Animal-care responsibilities encompass a variety of activities, including animal observations and environmental monitoring, feeding, watering, cage-changing and room sanitation, all of which are critical functions designed to promote a well-maintained animal housing area with minimal environmental variations. Consistent with the intent of the Animal Welfare Regulations (CFR, 1985), animal-care duties are intended to promote animal health and welfare, which is an essential component of good science and quality research.

There is no magical formula for determining the numbers and sizes of rooms required to support animal-use procedures. These are determined after close consultation with the users (i.e., investigative groups, animal-care and veterinary staff, the IACUC and the administrative staff), and ultimately must be balanced with the available budget. Consideration should include projections of the animal species and numbers to be used, animal colony health status, the type and number of experimental procedures, the duration and size of the studies, the frequency of performing various procedures, and the supplies and equipment required for the procedures. Another important factor to consider is the numbers of people and different user groups that must be accommodated. Answers to these questions will help to determine the types, numbers and sizes of procedures rooms that should be provided. It is useful to review past records to help determine trends and requirements, in conjunction with interviewing the current research and administrative staff, to gain a sense of projected requirements within the upcoming 3–5 years. Generally, animal husbandry or "care" requires support space but less procedure space, while animal studies or "use" requires more procedure space. Each procedure laboratory, regardless of known requirements, should have built-in flexibility to accommodate various types of research equipment as study needs changes. If centralized services are provided, a variety of animal-use procedures can be performed by the core staff, which in turn provide the necessary products (collected specimens, data, etc.) to the researcher. In some animal-care and -use programs, provision of core services can help to alleviate logistical challenges associated with heavy traffic flow from personnel representing different study groups, room-scheduling conflicts, and maintenance of procedure laboratory space, thereby reducing operating expenses.

Different types of procedure laboratories can be provided within a facility to allow for flexibility and efficiency. A well-designed facility should facilitate traffic flow between animal-care and animal-use personnel while minimizing the need for both groups to simultaneously occupy the same space. A smaller program with a limited number of different animal species and types of studies may be able to accommodate the schedules of focused research user groups, thereby requiring fewer procedure laboratories. On the other hand, a larger and more dynamic research program with multiple research groups and unpredictable schedules and needs, or a facility that houses many different animal species and/or large numbers of animals, will require more procedure laboratories and space.

A. Shared and Dedicated Procedure Laboratories

Procedures rooms have been referred to as "shared or dedicated" (Hessler, 1991). Different animal species or procedural activities may need to be separated and performed in dedicated procedure laboratories, whereas compatible animal species and procedures may be combined within shared procedure areas when schedules do not conflict. Figures 19-10a and 19-10b illustrate a generic shared procedure laboratory. Shared procedures laboratories may support several research animal-user groups and types of procedures, multiple animal holding rooms, and/or different animal species. Dedicated procedure laboratories support targeted studies that utilize animals with compatible health profiles from a single animal room or suite of animal rooms (Figures 19-11a, 19-11b). Assigned study personnel may keep unique or special research equipment and/or supplies in dedicated procedure laboratories. In some situations, it may be desirable to provide a combination of both dedicated and strategically located shared procedure rooms to accommodate the unexpected demands of a dynamic animal-care and -use program. The facility design difference between dedicated and shared procedure laboratories depends on the type of studies that will be performed, which to a very large extent is more a programmatic consideration rather than a facility design issue, differing primarily in the generally movable equipment required for conducting the studies. Careful planning with respect to procedure laboratory location, accessibility, utilities and equipment will facilitate optimal use of available procedural space by optimizing personnel time-management and minimizing unnecessary disturbances to the research animals.

Shared procedure laboratories can be situated between two or more animal holding rooms with access from a corridor,

directly from the animal holding rooms, from within a suite of several rooms with access via an anteroom, or from a service vestibule that is shared by the animal holding rooms and procedure area (Figure 19-12a). Likewise, dedicated procedure laboratories may also be positioned adjacent to the animal holding room, as an anteroom to an animal holding room, or as a room located within a suite of rooms used to house animals assigned to similar studies with compatible health status (Figure 19-12b). In any case, access into the procedure laboratory is ideally situated to minimize cross-traffic from the general facility circulation and also minimize extensive transport of animals from the holding rooms to the procedure laboratory. If sized properly, procedure laboratories provided as anterooms minimally impact the movement of animals in and out of the animal room, but may still result in scheduling conflicts between the animal-care and animal-use personnel when both groups attempt to perform their tasks simultaneously.

In some situations investigators may prefer to remove the animals from the animal facility and into their research laboratory to perform procedures. This may be necessary when the researcher has unique research equipment which is crucial to the studies but cannot be kept inside the animal facility for a number of reasons. The AWRs and PHS Policy indicates that animals held for more than 12 and 24 hours, respectively, are to have regulatory-compliant animal holding room provisions. The practice of removing the animals from the animal facility can create inherent concerns, and requires close review and approval by the IACUC, with ongoing monitoring. First, there is exposure of personnel not involved in animal-care and -use to animal allergens, infectious or zoonotic agents, or other contaminants, as well as the generation of unwarranted interest in the animals as they are being transported. In addition, the environment for which the animals are transported represents uncontrollable environmental variables that may impact the animals' physiological processes, making them more susceptible to disease agents that could be introduced into the balance of the animal colonies if the animals are returned to the animal facility, thereby potentially jeopardizing animal health and welfare and/or the interpretation of animal study data. Outside of the facility, animal-care providers may not be responsible for animal care. Animal-care providers are trained to assure that the animal-care and -use environment is appropriate to promote animal well-being and comply with regulatory mandates. Animal-care specialists are trained to observe and monitor animals for subtle behavioral abnormalities which may be attributed to a number of factors, including many environmental parameters. The animal-care facility is designed to provide the necessary physical environment, including air quality, temperature, humidity, ventilation, directional airflow, sound attenuation, light levels, pest control and security, while ultimately providing controlled environmental conditions for the research animals. These provisions can be difficult to achieve in a typical research laboratory environment. Thus, while removing animals from the facility may be necessary in some special circumstances, returning the animals at the conclusion of a study session can be problematic. Therefore, facility design features should include provisions to minimize the necessity for transporting animals away from the animal facilities.

A reasonable alternative might be to provide generic assignable research laboratory areas adjacent to or contiguous with but separate from the animal holding facility. Careful planning and design would permit the investigative study personnel to access this space without necessarily having to enter the animal facility, and yet allow the animal-care staff convenient access from within the animal facility to ensure provision of adequate animal care and environmental monitoring. Such an arrangement might be to provide a separate animal facility suite that is contiguous with both the research laboratory and animal facility, as possibly a wing or transition area within the research laboratory environment. Provisions for secured access into the main animal facility would incorporate existing mechanisms such as card readers, keypads, etc.

A worthwhile consideration for unique or special procedure laboratories is the use of animal cubicles (Hessler and Leary, 2002) that can be utilized in conjunction with both dedicated and shared procedure areas. Self-contained commercially prefabricated cubicles with single-sided or double-sided vertically sliding doors can be utilized in combined animal-care and animal procedure areas where high-volume animal-use activities require frequent interventions and/or close animal monitoring. Examples would include studies involving: hazardous agents (biological, chemical, radionuclides), where it is necessary to minimize the relocation of animals from one room to another for containment purposes (Figure 19-13); immunocompromised animals with transplanted xenografts used for biodistribution and imaging purposes; core transgenic animal facilities; and animals used in pharmacokinetic and toxicology studies involving multiple time-points for compound administration and tissue-sample collections, etc. (Figures 19-14, 19-15). This would permit procedure laboratories to be located adjacent to double-sided cubicles and accessed from a common corridor, or from a dedicated suite corridor with access to the animal cubicles from within the procedure room. The use of cubicles in this manner allows for flexibility and isolation while minimizing the distance associated with the transport of animals from the animal holding room to the procedure room. When multiple cubicles are provided, each cubicle is equivalent to an animal holding room; thus several smaller studies can be accommodated with efficient use of space while providing direct access to study animals from the procedure laboratory (Figure 19-14b) and also from the animal husbandry area (Figure 19-14c). Such an arrangement would help to address logistical concerns associated with both animal-care and animal-use personnel occupying the same space simultaneously.

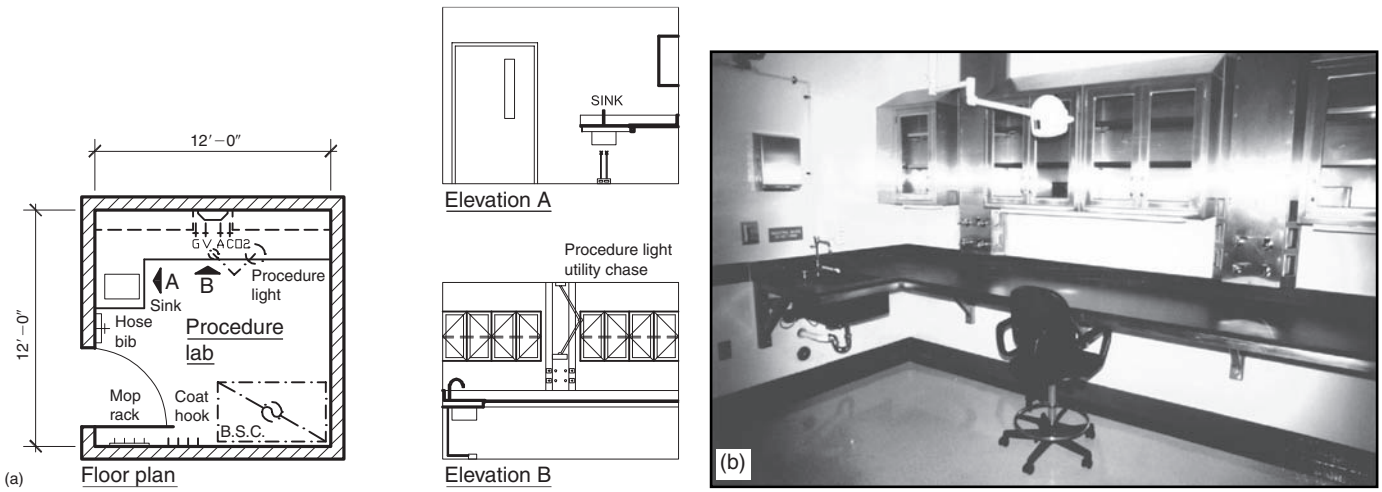


Fig. 19-10 (a) Typical procedure laboratory. (b) Typical shared procedures laboratory. Note that fixed equipment (upper cabinets and lower counter workspace) is wall mounted to facilitate cleaning. A sink, ceiling-mounted high-intensity examination light and two stainless-steel utility (moisture-resistant electrical outlets, air, vacuum, carbon dioxide and natural gas) service chases are shown.

BOX 19-6

FIGURE 19-10A: TEXT SUPPORT

Animal Procedure Laboratories – Room Needs

Room description: utilized by investigators as a research laboratory or space to perform procedures critical to the research program.

Adjacencies: in close proximity to or with direct access to or from the animal holding rooms.

Fixed Equipment

Hazardous fume collection: a back-draft table, Type II or III Biosafety Cabinet, fume hood or canopy hood to scavenge hazardous fumes utilized during the euthanasia and tissue specimen fixation processes. Back-draft tables may provide the most flexibility and convenience during procedures whereas biosafety cabinets or fume hoods can make it awkward or difficult to perform some activities.

Isolation cubicles: these can be used to provide added containment or isolation (Britz-Heldbrin, Inc.), and installed in dedicated procedure rooms that hose transgenic animals or where containment animal housing and procedure rooms may be combined.

Movable Equipment

Microscope table: there must be vibration-free work tables for use with sensitive equipment or microscopes as required (Kinetic Systems, Inc., Boston, MA).

Work Surfaces and Storage

Work surface: there must be adequate standing-height workspace for laying out supplies, instruments, and materials for use in procedures to be performed.

Fold-down work surface: when space is limited, a custom stainless-steel fold-down work surface can be useful and provide flexibility within a procedure room. The fold-down table can be laid flat against the wall to allow additional space for biosafety cabinets, cage racks, etc.

Carts or tables: provision as needed, as supplemental work surfaces while working at the necropsy tables.

Storage: adequate storage space should be provided for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient. They can be assigned to different user groups stocked with supplies and stored in a designated area of the facility, and relocated into the use space as needed (Figure 19-3f) (Herman Miller, Inc., Zeeland, Michigan).

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

BOX 19-6

CONTINUED

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Accessories

Marker board

Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD)

Coat hooks.

Doors

There should be one 3′8″ min. wide by 7′0″ high door with view port. Controlled access to this room from the animal facility should be considered.

Plumbing

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sinks should be considered.

Hose bib, hose reel and floor drain: the provisions of a high-pressure hose bib with a temperature gauge and quick-disconnect and hose reel facilitates the removal of gross debris prior to sanitizing. The hose reel should be located adjacent to the hose bib and provide enough hose length to comfortably wash down the entire room. The hose should also be provided with quick disconnects for the attachment of disinfectant solution containers. The floor should be sloped towards the drain, which should be centrally located within the room while out of the path of major circulation. The drain should be equipped with a self-priming valve to ensure that sewer gases are blocked from entering the room.

Gases: provision of air (A), vacuum (V), oxygen (O_2) and carbon dioxide (CO_2) to the surface-mounted utility chases. Individualized cylinders may be provided within the room for smaller programs, but adequate space must be provided and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas for minimal interruption as the cylinders empty. If a house system is provided then an adequate number of outlets should be provided for each gas required for the anticipated procedures.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Under-cabinet task lighting is required to facilitate and obtain 100 foot-candles at the work surface. There should be procedure light at the ceiling for performing procedures and eliminate shadows (Skytron, Grand Rapids, MI; ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration to the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within a lab and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of bench top work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment will be located at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room that will be connected to a file server. Provisions for wireless computer access

(*Continued*)

BOX 19-6

CONTINUED

terminals are becoming more prevalent and if provided by the facility, data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety, as well as a connection to the building paging system which may be used in times of building-wide emergency or locating individuals within the facility

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 12 changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining spaces should be negative. Each isolation cubicle should be provided with a dedicated exhaust if room air is not used for isolation temperature control (ASHRAE, 2003).

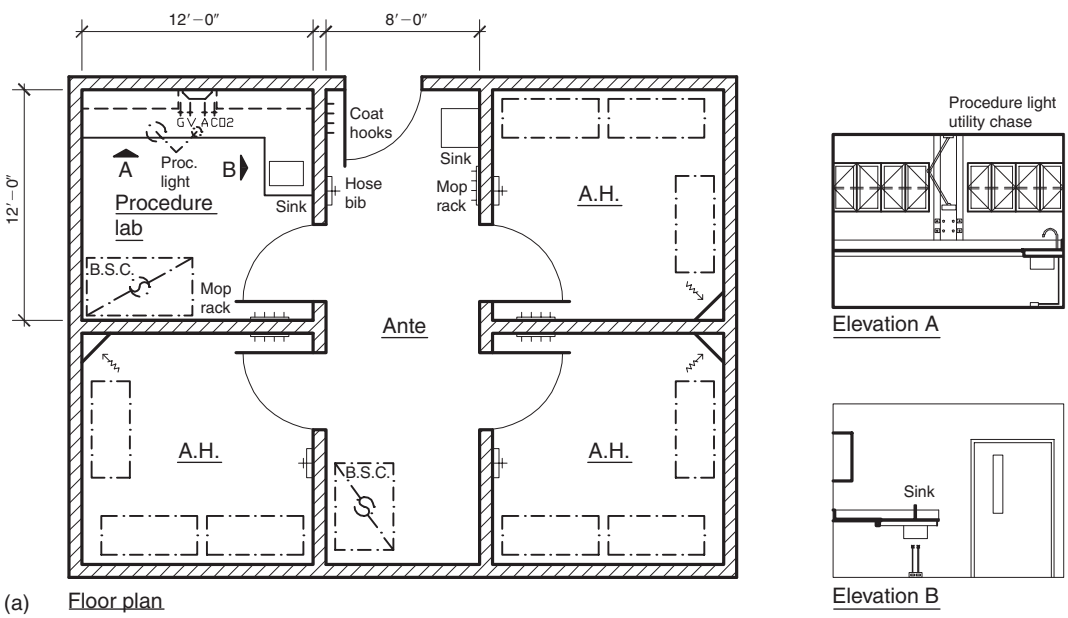
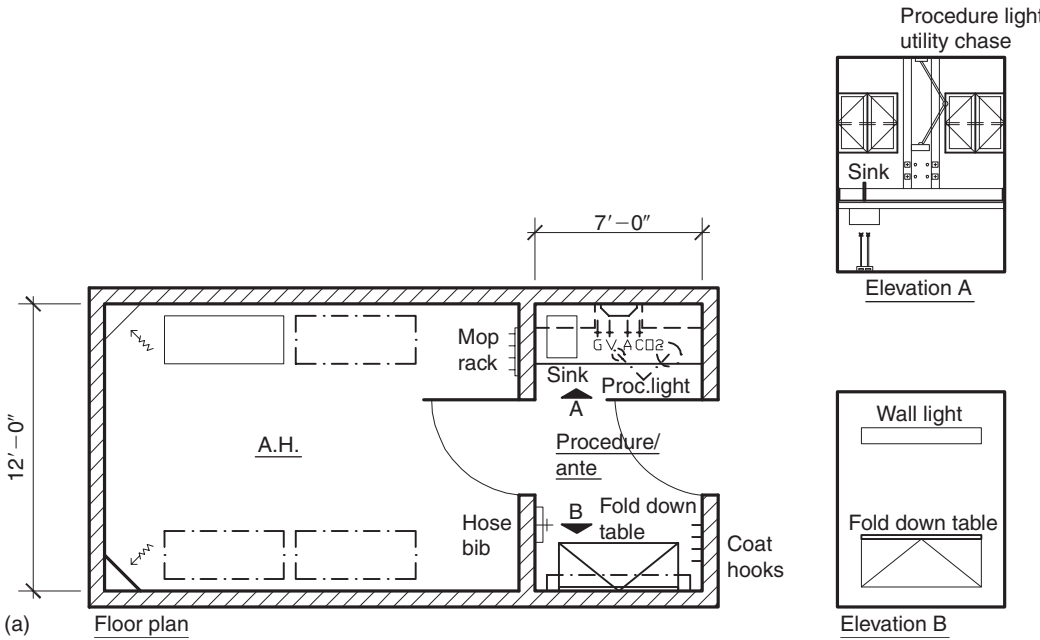


Fig. 19-11 (a) Animal holding suite with procedure laboratory. (b) Suite vestibule. This is an entry vestibule into four rooms (one procedure laboratory and three animal holding rooms). Suite arrangements allow for compartmentalization of compatible studies to utilize shared procedures laboratories.



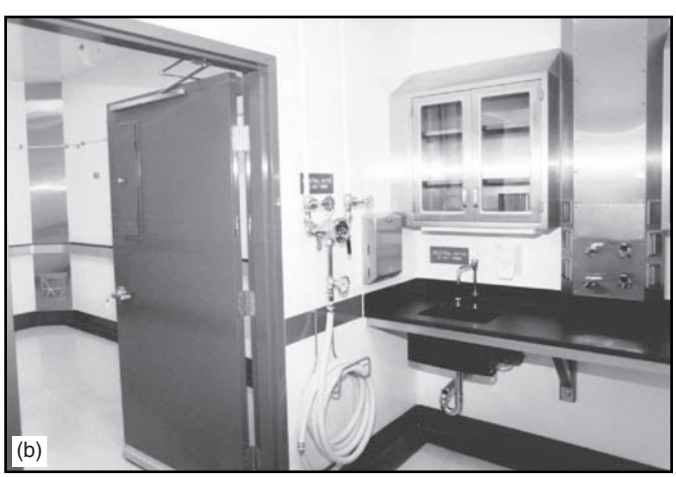


Fig. 19-12 (a) Procedure laboratory/anteroom. (b) Dedicated procedures laboratory. This is a view of an anteroom looking into an animal holding room (opened door). Wall-mounted upper cabinets and lower work surface with sink, and a stainless-steel utility (moisture-resistant electrical outlets, air, vacuum, carbon dioxide and natural gas) service chase are shown. Note that none of the casework extends to the finished floor, which facilitates cleaning.

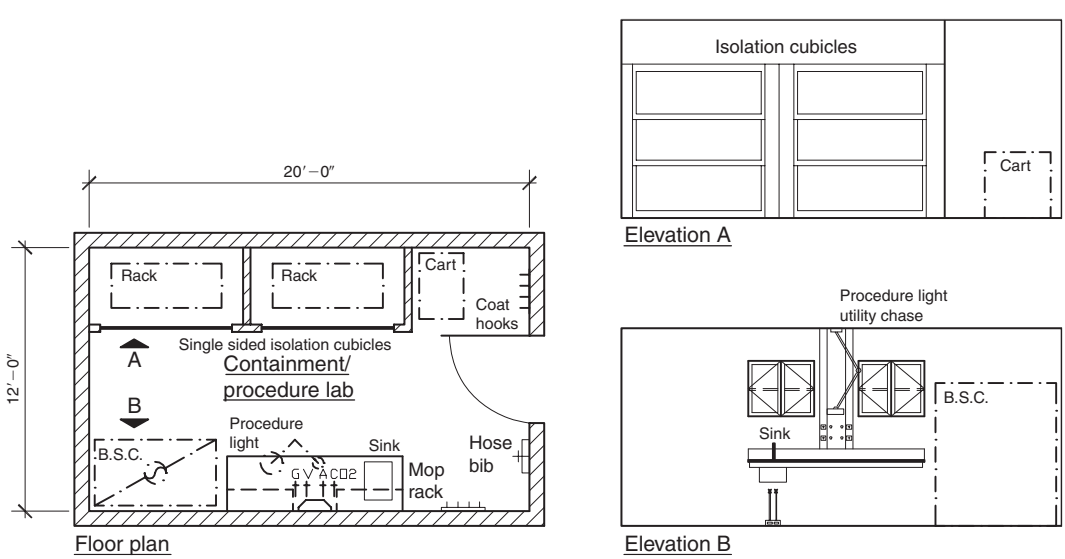


Fig. 19-13 Containment/procedure laboratory.

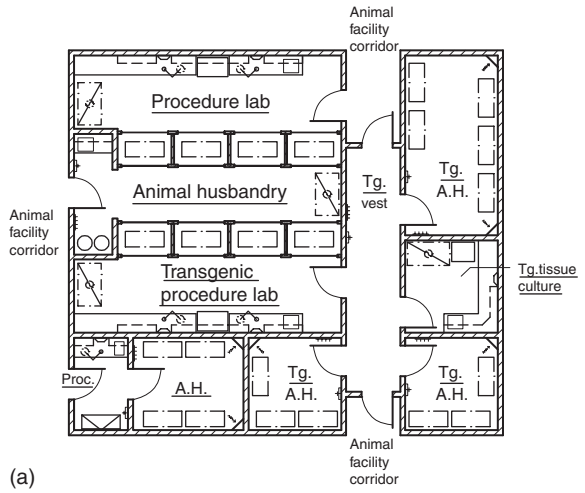
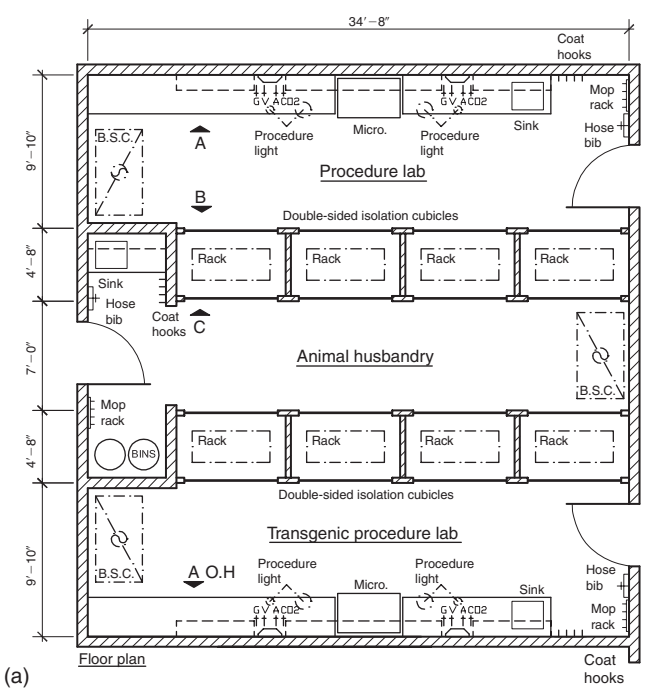


Fig. 19-14 (a) Procedure laboratories and animal husbandry suite. (b) Double-sided cubicles procedures laboratory. There are four 7′ × 4′ cubicles (left), wall-mounted upper cabinets, lower work counter with vibration-free table, and two stainless-steel utility (moisture-resistant electrical outlets, air, vacuum, carbon dioxide and natural gas) service chases, all on the right-hand side. A sink is located adjacent to the door. Each cubicle has a second vertical sliding door on the opposite side (see Figure 19-14(c)) to accommodate animal husbandry service activities. (c) Double-sided cubicles animal husbandry space. There are eight 7′ × 4′ cubicles (four on each side) and an animal transfer workstation against the back wall.



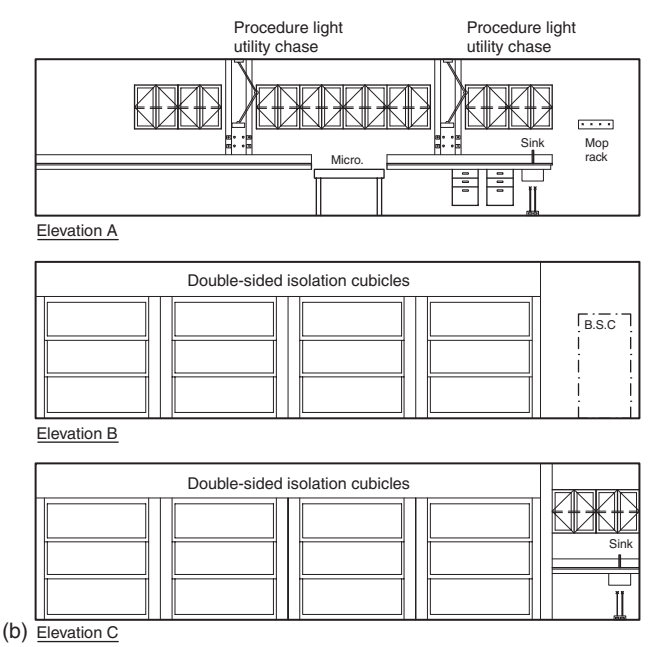


Fig. 19-15 Procedure laboratories and animal husbandry room.

B. Behavioral Laboratories

Neuroscience or behavioral studies may require special equipment and various equipment arrangements in addition to unique environmental controls for parameters such as sound, lights, gravity, atmospheric pressure, etc., to satisfy experimental designs. Involvement of the research scientists early during facility planning will help to identify particular concerns that will help ensure incorporation of unique features. The use of various types of equipment that can be custom built or are commercially available (e.g., animal behavior chambers, running wheels, photocell arrays, mazes, video cameras and monitors, etc.) are generally utilized in the laboratory. The research scientists can provide the most accurate information that will highlight special facility design requirements. A separate discussion of noise control is provided below, following discussion of the rodent sleep research laboratory and the rodent neurobehavioral testing laboratory. This discussion will help in the understanding of facility provisions to achieve appropriate noise control. Noise control is a key element to include in the facility planning process. The acoustical environment can have a profound impact on overall efficiency and productivity by its effects on personnel and animals (Pekrul, 1991). Likewise, the consequences of light (periodicity, intensity and wavelength) have been shown to alter both behavioral and physiologic parameters in many species (Lipman and Perkins, 2002). The same facility design principles provided for rodent neurobehavioral laboratories are also applicable to areas involving other animal species (e.g., non-human primates) that are used in similar studies; however, planning must incorporate provisions to accommodate the animal species and the particular research needs.

1. *Rodent Sleep Laboratory*

A determination of the size and layout of a rodent sleep research laboratory is contingent on the size of the research program and the number of people that will have to be accommodated. Laboratory arrangements may vary from an appropriately sized animal housing room with an anteroom adapted to suit the research use needs, to a suite of several rooms. Discussions with the end-users (research personnel and animal-care personnel) and the Institutional Animal Care and Use Committee will facilitate provisions to satisfy institutional and regulatory requirements. Functional areas of a sample laboratory include an animal housing room modified for sleep recording, an area to perform survival surgical procedures and tissue collection (temporally separated), and an area for data collection and video monitoring. An example of a rodent sleep laboratory that utilizes a modified animal holding room with an anteroom is illustrated in Figure 19-16. As presented, the anteroom is divided, and serves to support both rodent surgical procedures and also data collection and video observation and monitoring. The surgery area is readily converted into a tissue dissection area through the use of movable equipment. The animal room is modified to accommodate video-recording cameras and animal behavior chambers. A middle entry/exit vestibule between the anteroom and animal holding room permits personnel movement between the rooms with minimal disturbance to the animals on study. This discussion should illuminate the necessity for providing special procedure laboratories in some facilities and, likewise, of providing storage space for research equipment when it is not being used.

The surgery procedures area is utilized for survival surgery to implant electrodes to monitor brain and muscle activities that are used to identify and distinguish non-rapid eye movement (non-REM) sleep and REM sleep from the waking state. The animal would be anesthetized using gas anesthesia (e.g., isofluorane in oxygen) throughout the entire surgical procedure, therefore provisions for anesthetic gas scavenging must be addressed. A stereotaxic instrument (movable) is required to secure the animal's head in a fixed position during surgery in order to optimize placement of electrodes. Following electrode placement, which is stabilized with a headcap, the animal is released from the stereotaxic apparatus and a femoral vein catheter is placed with the assistance of dissection microscope. The catheter is used to euthanize the animal while it's in the desired sleep state without touching it, and thereby not affecting the chosen behavior. A movable workstation is used during surgery to allow one person to begin implanting EEG/EMG electrodes into the next rat while another person implants a femoral catheter into a rat already fitted with EEG/EMG electrodes.

Tissue dissection and collection procedures utilize the space previously used for survival surgery. After the animal has been euthanized in the animal behavioral chamber by remote administration of euthanasia solution, the brain must be quickly removed from the body to gain access to the tissue from individual brain regions chosen for the analysis of mRNA and protein expression. To accomplish this, a tissue dissection area is assembled in the surgery area on the day of animal euthanasia. The surgery area is transformed into a tissue dissection area by removal and temporary storage of the anesthesia machine, stereotaxic set-up and the workstation from the area.

A data-collection and video-monitoring area is also located within the anteroom, but in an area separate from the animal procedure area. This area holds the equipment used to monitor, digitally capture and electronically store the electrophysiological and observational measures of sleep–wake behavior. Provisions must be made to accommodate communication between the recording equipment contained in the animal housing room and the data-collecting equipment in the anteroom.

The animal housing and sleep-recording room (inclusive of animal behavioral chambers) serves two purposes; it is used to house the animals individually after surgery, and also to execute the experimental protocols. As described, this sleep lab can record the behavior of multiple animals simultaneously (i.e., up to 16 animals per rack recording system). The equipment kept inside the room falls into two general categories: sleep-recording equipment and video-monitoring equipment.

The individual recording electrodes that pass the electrophysiological signals from each animal are connected by means of a bundled single cable connected to electrode headcaps. These individual cables, in turn, send the raw analog signals from each animal to an amplifier system. The amplifiers' cables are bundled together within conduits bilaterally located in the ceiling, where the analog signals are transformed to a digital output signal via computer software communication located in the anteroom. Each amplifier transforms the EEG/EMG signal for up to 16 animals. The cameras that are used to observe each animal are individually mounted. Cables carrying this information are also bundled within conduits to connect the TV/video monitors, which can also depict up to 16 animals per video screen. The EEG and EMG recordings are monitored in

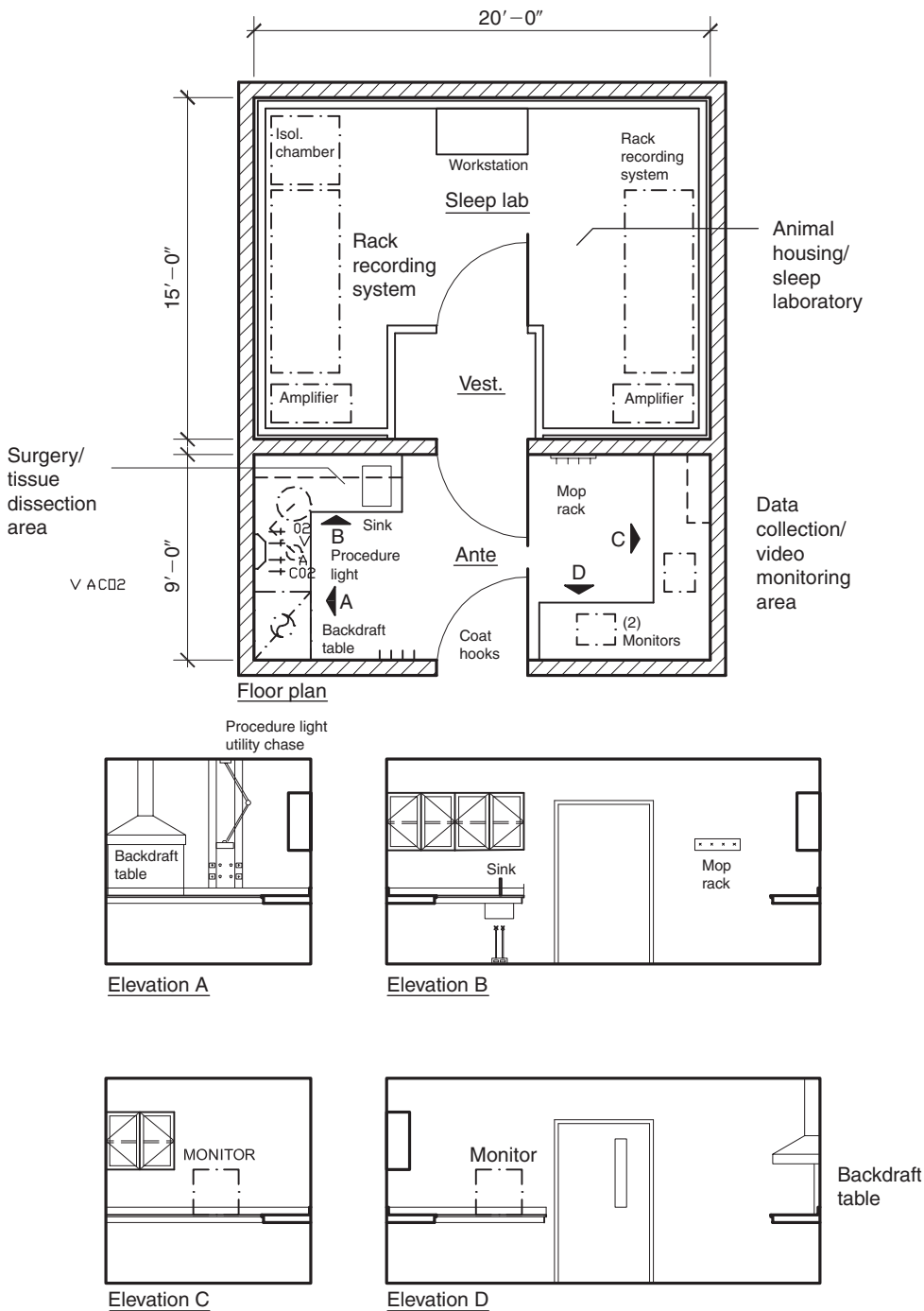


Fig. 19-16 Sample rodent sleep laboratory.

real time, visualized on the computer screens and simultaneously stored to a disk via a sleep-scoring program. TV/video monitors located within this area also allow for observation of animal behavior in real time.

The vestibule entry into the sleep-recording room provides for sound attenuation, light control and air pressure stabilization in order to minimize arousing the animals when personnel enter and exit the animal housing room. The door junctions are equipped with heavy cushioning gaskets to attenuate sound and prevent light transmission. In addition, a through-the-wall air transfer duct with an elevated opening in the animal room connected to a low opening in the vestibule entry is provided to equalize room air-pressure changes between the animal housing area and the anteroom as the door is opened and closed. Careful control of air pressure relative to the adjacent room allows the ability to dissect tissue in the anteroom on the day of euthanasia while keeping the smell of blood from entering the behavioral area. It is critical to locate sleep laboratories in low-traffic and low-noise areas in order to minimize disruption caused by activities in adjacent areas.

BOX 19-7

FIGURE 19-16: TEXT SUPPORT

Rodent Sleep Laboratory – Room Needs

Rodent Sleep Laboratory Suite

Room description: a sample rodent sleep laboratory suite is composed of three spaces:

1. *Surgery/Tissue Dissection Area*-Major surgery is performed to implant electrodes to monitor brain and muscle activities. At the conclusion of the live sleep study and immediately after euthanasia surgery procedures are performed to provide end of study data critical to the research. This area can be located in the same room as the Data Collection/Video Monitoring Area.
2. *Data Collection/Video Monitoring Area*-Area utilized to house the equipment used to monitor, digitally capture, and store the electrophysiological and observational measures of sleep-wake behavior. This area can be located in the same room as the Surgery/Tissue Dissection Area.
3. *Animal Housing/Rodent Sleep Laboratory*-Used to house the animals after implantation of electrodes and monitors and execute experimental protocols.

Adjacencies: a remote, low-traffic location in the facility as far as possible from noise-generating animal species housing rooms or equipment such as cage-wash and mechanical rooms is preferable to help facilitate maintaining a quiet environment essential to the research protocols.

Fixed Equipment

Surgery/Tissue Dissection Area

Hazardous fume collection: a back-draft table, Type II or III Biosafety Cabinet, fume hood or canopy hood to scavenge hazardous fumes utilized during the euthanasia and tissue specimen fixation processes. Back-draft tables may provide the most flexibility and convenience during procedures whereas biosafety cabinets or fume hoods can make it awkward or difficult to perform some activities.

Lighting: there should be procedure lighting at the ceiling for performing surgeries at the surgery/tissue dissection area (Skytron, Grand Rapids, MI; ASHRAE/IESNA, 2004).

Animal Housing/Rodent Sleep Laboratory

Amplifier system: the animal housing area is equipped with amplifier systems for processing of electrophysiological signals from the animals.

Movable equipment

Surgery/Tissue Dissection Area

Stereotaxic instrument: for rodent neurosurgery with accessories that will accommodate inhalation anesthesia systems.

Anesthesia delivery system: tabletop inhalation anesthesia system.

Balance: a digital balance is used to record the weight of each rat before surgery and on the day of sacrifice.

Data-Collection/Video Monitoring Area

TV/video monitors: video equipment includes cameras to individually monitor/record sleep–wakefulness of each animal for baseline measures as well as the day of euthanasia.

Computers: for data collection and analysis of EEG/EMG recordings.

Animal Housing/Rodent Sleep Laboratory

Workstation: a movable cart can be used as a workstation for animal-care and catheter maintenance activities.

(*Continued*)

BOX 19-7

CONTINUED

Isolation chamber: use of an isolation chamber permits reversal of the lighting schedules for subsets of animals without disturbing the remainder of the animals habituated to the ambient light source and schedule.
Video monitoring: video surveillance systems with multiplexers, monitors, recorders, infrared cameras and accessories for simultaneous monitors the number of animals included in the studies.
Rack recording system: animal housing racks with the capability of connecting the sleep recording information gathered from the animal to the amplifier within the room.

Work surfaces and storage

Surgery/Tissue Dissection Area

Work surface: there must be adequate standing-height workspace for laying out supplies, instruments, and materials for use in procedures to be performed.
Storage: adequate storage space should be provided for various supplies and equipment utilized for surgery and dissection procedures. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f) (Herman Miller, Inc. Zeeland, Michigan).

Data-Collection/Video Monitoring Area

Work surface: there must be adequate sitting-height workspace for computers, equipment, supplies and materials for use in the data-collection/video monitoring area.

Animal Housing/Rodent Sleep Laboratory

Work surface: movable tables should be available for use as workstations and as layout space for equipment, supplies and materials for use in the rodent sleep laboratory.

Animal-Care Needs

Surgery/Tissue Dissection Area

None required.

Data-Collection/Video Monitoring Area

None required.

Animal Housing/Rodent Sleep Laboratory

Animal feed and watering capability to match the requirements of the balance of the animal holding facility should be provided.

Accessories

Marker Board

Cleaning implements holding rack (“mop rack”) (Life Science Products, Inc., Chestertown, MD)
Coat hooks.

Doors

Surgery/Tissue Dissection and Data-Collection/Video Monitoring Areas

There should be a 3′8″ min. wide by 7′0″ high door with view port to the animal facility corridor. Controlled access to this room from the animal facility should be considered.

Animal Housing, Sleep Recording Room

The doors to the entry vestibule of the animal housing room should be 3′8″ min. wide by 7′0″ high to facilitate equipment movement. In addition, the doors should be hermetically sealed due to the positive airflow from the animal housing area to the anteroom, which help minimize air pressure changes upon entry and exit. To additionally ensure that noise is kept to a minimum, the doors to the entry vestibule should be equipped with a non-rotating handle with no locking mechanism.

Windows

No windows should be provided in any of the sleep study spaces containing animals.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.
Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be

BOX 19-7

CONTINUED

utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Special Construction

There should be full-height sound-attenuating walls at animal housing, sleep recording room, with an entry vestibule to mitigate noise generated in the surgery and data collection rooms and animal facility.

Plumbing

Surgery/Tissue Dissection Area

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sinks should be considered.

Gases: air (A), vacuum (V), oxygen (O_2) and carbon dioxide (CO_2) to the surface-mounted utility chases. Individualized cylinders may be provided within the room for smaller programs, but adequate space must be provided and provisions for a gas cylinder rack to provide appropriate restraint (Safe-T-Rack Systems, Inc., Rocklin, CA). It is recommended that two cylinders be provided for each gas for minimal interruption as the cylinders empty. If a house system is provided then an adequate number of outlets should be provided for each gas required for the anticipated procedures.

Data-Collection/Video Monitoring Area

None required.

Animal Housing/Rodent Sleep Laboratory

None required.

Electrical

Surgery/Tissue Dissection and Data-Collection/Video Monitoring Areas

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Under-cabinet task lighting is required to facilitate and obtain 100 foot-candles at the work surface. There should be a procedure light at the ceiling for performing surgeries and eliminate shadows (Skytron, Grand Rapids, MI; ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration to the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within a lab and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of bench top work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment will be located at perimeter walls.

Animal Housing, Sleep Recording Room

Lighting: rodent sleep varies as a function of the time of day, with animals spending~60–70 percent of the "day time" asleep. In the laboratory, this time is simulated by maintenance of a 12-hour lights-on, 12-hour lights-off schedule. Lighting should include dim red lights to allow reversal of the 12-hour light schedule. In mammals, the most potent mediator of circadian/biological rhythm entrainment is a change in light exposure in the environment. Lipman and Perkins (2002)provide a well-documented discussion on this topic. As such, a combination of cool-white fluorescent (greater than 200 lux) and dim red light (less than 1 lux; wavelength greater than 600 nm) fixtures are in place in laboratory to control ambient light effects on the animals' behavior. White lights are on continuously for a 12-hour period (8 am–8 pm) and off (dim red light is in place that is not perceived by the rats, yet allows workers to perform maintenance duties) for a 12-hour period (8 pm–8 am). In contrast, there is evidence that dim far-red light (1 lux at 625 nm) exposure is associated with an increased circadian period in some mouse strains. Hofstetter *et al*. (2005)suggest that red-light background illumination should be avoided, and that indicator diodes on passive infrared sensors should be switched off to prevent increases in the period of daily locomotor activity in mice. Lighting is monitored and controlled by the building management system (ASHRAE/IESNA, 2004).

(*Continued*)

BOX 19-7

CONTINUED

Power: all electrical outlets should have waterproof covers and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration to the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within a lab and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 4′–6′ of wall length where floor-mounted equipment will be located at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room that will be connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. A silent phone equipped with a light strobe to announce incoming calls to the laboratory should be provided in order to ensure silence and minimize disturbance to the animals located in the animal housing area.

Mechanical

Surgery/Tissue Dissection and Data-Collection/ Video Monitoring Areas

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 12 changes of 100 percent outside air should be provided. Directional air flow in relationship to the corridor and animal housing room should be negative (ASHRAE, 2003).

Animal Housing/Rodent Sleep Laboratory

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 10–15 changes of 100 percent outside air should be provided. Directional air flow in relationship to the surgery/tissue collection area should be negative (ASHRAE, 2003).

2. *Rodent Neurobehavioral Testing Laboratory*

The functional observation battery (FOB) provides a systematic neurologic assessment for rodents involving a neurologic examination with numerous behavioral measures (NRC, 2003). The space requirements for neurobehavioral testing should be consistent with the number and types of activities performed, as well as the numbers of animals to be tested in one session. The testing laboratory should allow for easy movement of animal handlers, cage racks, and laboratory tables, workbenches and equipment used for testing procedures. Figure 19-17 provides a representative schematic room layout for FOB and motor activity testing procedures. Neurobehavioral test procedures may be performed in either a designated laboratory or a designated animal room. One consideration is whether the testing laboratory has adequate space. In general, the space is considered adequate when it minimizes disruption and relocation of the test animals between different rooms in order to perform the testing procedures.

Animals are sensitive to ongoing activities and other stimuli that occur in their environment. Since exposure to non-test stimuli may result in an animal altering its response to a test stimulus, it is important to minimize background non-test stimuli in the testing laboratory as much as possible. Other than effective noise control and the provisions of standard laboratory animal facility design criteria (ILAR, 1996), there are few special architectural requirements for neurobehavioral test facilities. Considerations for the laboratory's location should be focused towards minimizing external acoustical and mechanical (e.g., vibration) stimuli. These considerations do not necessarily require structural changes to a testing

laboratory, but can instead require that neurobehavioral studies be conducted in less disruptive locations – for example, a room located in a designated suite or in a low-traffic and low-noise area.

Lighting requirements for nocturnal rodents (e.g., rats and mice) may be a particular concern when conducting tests for neurobehavioral endpoints. Light periodicity, intensity and wavelength can have a profound impact on animal behavior and physiology (Lipman and Perkins, 2002). Depending upon the research study design, overhead room lighting should allow for reversal of the light–dark cycle or reduced lighting conditions, which may be controlled by the building management system. It may also be helpful, if possible, to have task lights available on laboratory benches and tables. One method of mimicking "dark" conditions with nocturnal rodents has been the provision of lighting in the red to orange spectrum (600–685 nm). Special light bulbs or light-bulb sleeves may be available to convert standard light fixtures and bulbs to create an appropriate lighting environment. However, such arrangements may not be suitable for all studies requiring dark conditions. Hofstetter *et al*. (2005) reported that red light as background illumination should be avoided during studies of circadian cycles with mice. It was observed that dim red-LEDs (light-emitting diodes) illuminated intermittently (1 lux at 652 nm) increased the circadian periods of mice. Behavior chambers that are designed to block all unwanted illumination can be utilized for some studies; however, it may be necessary to construct an entire room to meet this same criterion for other studies.

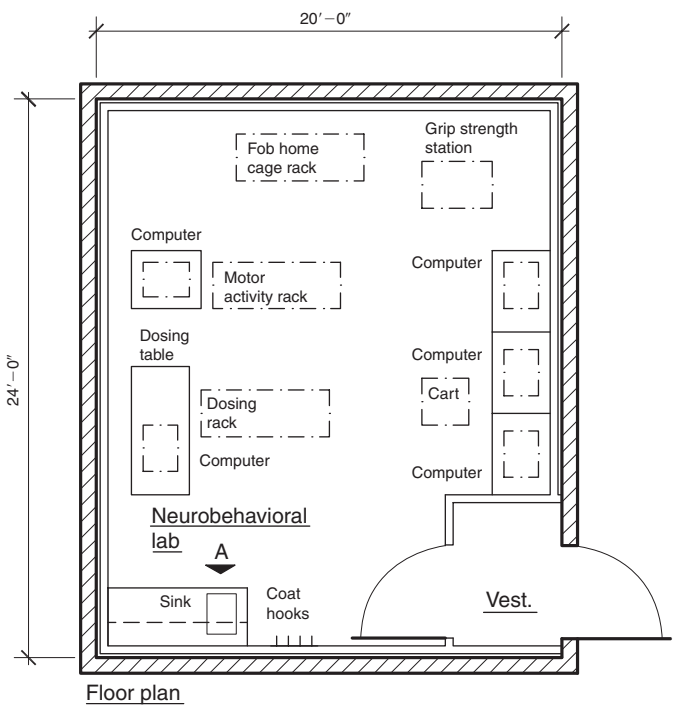


Fig. 19-17 Sample rodent neurobehavioral laboratory.

Plumbing fixtures and water access are concerns when water-based neurobehavioral procedures are to be performed (e.g., water mazes). Consideration should be given to provision of adequate space for set-up and maintenance of water-based testing devices (e.g., mazes), access to water for cleaning and filling of the devices, and sufficient floor drainage and slope to control spillage either during the testing procedure or during equipment cleaning.

There is a variety of commercially available and custom-built specialized equipment that may be used in neurobehavioral testing. In addition to testing equipment such as various kinds of mazes (including water mazes), running wheels (e.g., a rotorod), open-field areas and passive avoidance units (NRC, 2003), many laboratories utilize data-capture software which may or may not require computer connections to a centralized server. The research investigators should participate in the planning laboratories to support neuroscience and behavioral studies.

BOX 19-8

FIGURE 19-17: TEXT SUPPORT

Rodent Neurobehavioral Laboratory – Room Needs

Room description: utilized by investigators as a research laboratory or space to perform functional operational battery tests critical to the research program.

Adjacencies: remote, low-traffic location in the facility as far as possible from noise-generating animal species housing rooms or equipment such as cage-wash and mechanical rooms is preferable to help facilitate maintaining a quiet environment essential to the research protocols.

Movable Equipment

Various animal housing racks, supporting computer equipment and computer workstations: specific to the study to be performed.

(*Continued*)

BOX 19-8

CONTINUED

Movable carts: for use as supplemental work surfaces for laying out equipment which supports the studies.

Work Surfaces and Storage

Work surface: there must be adequate sitting-height workspace for computers, equipment and materials for use in the neurobehavioral laboratory.

Storage: there should be adequate storage space for various supplies. Lockable wall-mounted storage units that are movable and capable of withstanding high-temperature sanitation procedures are useful and convenient (Figure 19-3f) (Herman Miller, Inc., Zeeland, Michigan).

Animal-Care Needs

Animal feed and watering capability to match the requirements of the balance of the animal holding facility.

Accessories

Marker board

Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD)

Coat hooks.

Doors

There should be one 3′8″ min. wide by 7′-0″ high door. Controlled access to this room from the animal facility should be considered.

Windows

No windows should be provided in any of the behavioral study spaces containing animals.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents, disinfectants and high-pressure water. Curbs, guardrails, bumpers and corner guards should be utilized to protect from impact damage (Life Science Products, Inc., Chestertown, MD).

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Special Construction

There should be full-height sound-attenuating walls with an entry vestibule at animal housing neurobehavioral laboratories to mitigate noise generated in the animal facility.

Plumbing

Sinks: there should be one sink, with hot and cold water, for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sink should be considered.

Electrical

Lighting: rodent sleep varies as a function of the time of day, with animals spending ~60–70 percent of the "day time" asleep. In the laboratory, this time is simulated by maintenance of a 12-hour lights-on, 12-hour lights-off schedule. Lighting should include dim red lights to allow reversal of the 12-hour light schedule. In mammals, the most potent mediator of circadian/biological rhythm entrainment is a change in light exposure in the environment. Lipman and Perkins (2002) provide a well-documented discussion on this topic. As such, a combination of cool-white fluorescent (greater than 200 lux) and dim red light (less than 1 lux; wavelength greater than 600 nm) fixtures are in place in the laboratory to control ambient light effects on the animals' behavior. White lights are on continuously for a 12-hour period (8 am–8 pm) and off (dim red light is in place that is not perceived by the rats, yet allows workers to perform maintenance duties) for a 12-hour period (8 pm–8 am). In contrast, there is evidence that dim far-red light (1 lux at 625 nm) exposure is associated with an increased circadian period in some mouse strains. Hofstetter *et al*. (2005)suggest that red-light background illumination should be avoided, and that indicator diodes on passive infrared sensors should be switched off to prevent increases in the period of daily locomotor activity in mice. Lighting is monitored and controlled

BOX 19-8

CONTINUED

by the building management system (ASHRAE/IESNA, 2004).

Power: all electrical outlets should have waterproof covers and be of the GFI type, which allows short-circuiting of the system should it come in contact with water. It is recommended that outlets be installed horizontally as opposed to vertically and provided with two covers, one for each outlet. This design prevents water penetration to the second outlet when the use of only one outlet is necessary. Due to the increased use of electronic equipment within a lab and to facilitate electrical cord management, an adequate number of electrical outlets should be provided. It is recommended that one duplex outlet be provided for each 18″–24″ of bench top work surface and one duplex outlet for each 4′–6′ of wall length where floor-mounted equipment will be located at perimeter walls.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room that will be connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. A silent phone equipped with a light strobe to announce incoming calls to the laboratory should be provided in order to ensure silence and minimize disturbance to the animals located in the animal housing area.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 10–15 changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining spaces should be negative (ASHRAE, 2003).

3. *Special Sound Control Considerations*

Sound control is an important consideration in behavioral studies. Good control of sound from outside sources is important; likewise, there may also be a need to reduce the reverberation of sound from sources within the room. It is highly recommended that an acoustical professional be employed to analyze particular space requirements and to provide guidance, as many factors impact the ability of a facility to either block or absorb noise. The sound transmission coefficient (STC) measures the ability of a material or construction assembly to block noise (barrier effect), which is mass dependent. However, the ability of a material to absorb noise is determined by its noise reduction coefficient (NRC), which is achieved with a porous material that has a high sound absorption rate (such as mineral wool). A well-designed sound-control room for behavioral research studies will reduce noise (sound transmission) from outside sources (i.e., have a high STC rating) and also reduce noise reverberation from inside the room if desired (i.e., have a high NRC rating) (Gypsum Association, 2003; Acoustical Design Group, Inc.; Netwell Marketing, Inc.).

Effective room design to meet the requirements of behavioral research must begin by first determining or defining the frequency range and decibel rating of the greatest anticipated noise to be blocked. Afterwards, the study animals' hearing frequency ranges should then be defined. Hessler and Leary (2002) and Lipman and Perkins (2002) provide discussions on the impact of noise on experimental animals. It would be cost-prohibitive to provide sound control within a room from all decibel sources and hearing frequency ranges, but, given these known parameters, an effective wall can be constructed that has appropriate STC and NRC ratings. Research investigators often resort to retrofitting an existing space that has not been designed for specified levels of noise control. Frequently, open- or closed-cell foam and other porous materials are attached to the wall; however, this technique compromises the ability of the wall and sound-deadening material to be appropriately sanitized, and has other inherent drawbacks. Open-celled foam, which is excellent for absorbing noise, is difficult to disinfect. In addition, foam, although effective for absorbing noise, does not block noise, and therefore noise can still intrude from adjacent spaces.

Flanking noise is noise that enters the space via penetrations in the wall or at junctures of similar and dissimilar construction materials. All flanking-noise pathways must be blocked in order to provide walls with a high STC rating. The construction of the room perimeter walls by use of a double stud wall and provision of three layers of water-resistant gypsum or cement board at each side, and mineral-wool insulation within the cavities, will provide a high STC rating if the precautions to prevent flanking noise are incorporated into the facility design. To facilitate reducing flanking noise, it is imperative to provide an acoustical sealant at all dissimilar surfaces, stagger the joints of the gypsum board, and not install any devices (such as electrical, data and temperature control) back-to-back, but rather in staggered stud locations. A sufficient concrete masonry unit (CMU) sound wall can also be achieved by constructing two CMU walls side by side with a 2-inch gap between them and infilling the 2-inch gap, as well as all non-grouted cells within the CMU, with a sound-absorbing material.

Careful attention must also be given to the space above the ceiling for proper noise control from adjacent spaces. The STC rating of the ceiling is greatly increased if there are full-height walls to the bottom of either the floor above in multi-storey buildings, or the roof above, and if considerable interstitial space is provided. To provide an effective ceiling-level noise barrier, use of ceiling joists and a single layer of gypsum board may be sufficient. An acoustical sealant should be applied at the perimeter of the ceiling plane at the wall to account for movement and to prevent flanking noise. Mechanical system and lighting penetrations at the ceiling must also be addressed. Provision of several turns in the HVAC ductwork and the use of filters at the diffuser grilles help minimize noise transfer from adjoining spaces. Utilization of flush-mounted class-A rated fluorescent lights with a gypsum board tent above the ceiling space provides good protection from noise.

Doors and windows can also compromise the integrity of a sound-controlled laboratory. However, observation windows may be provided from an adjoining room without seriously affecting the sound-controlled room if the observation room is also constructed to the same sound-control standards as the sound-controlled laboratory, and noisy activities are restricted. In lieu of sound-retarding doors, which can be quite expensive, entering the laboratory through a double-door vestibule and equipping the doors with sound gasketing provides a less expensive alternative without much compromise in performance.

A very effective method of obtaining an acceptable NRC rating for sound absorption within the laboratory can be achieved with utilization of commercially available sound panels (Netwell Marketing, Inc.). These high-density fiberglass-core hardboard panels that are fully encapsulated in a tedlar (polyvinyl fluoride) film are available commercially, and can be applied to the ceiling or walls, or used as a hanging noise-baffle system. The thickness of these class-100 clean-room approved heat-sealed tedlar-faced panels varies depending on the amount of sound that is to be absorbed. Custom sizes are available.

VII. IMAGING LABORATORIES

Ultimately, the goal of biomedical investigations is to move research discoveries from the laboratory bench to the patients' bedside. Utilization of animal models continues to be essential in contributing to that goal. A number of imaging techniques are used in animals for diagnostic and experimental purposes. Imaging techniques include radiography, fluoroscopy, ultrasonography, magnetic resonance imaging (MRI), computerized axial tomography (CAT), positron emission tomography (PET) and single-photon emission tomography (SPECT). The development of all of these techniques has utilized laboratory animals (Adams, 2002). Advances in imaging technologies have provided powerful, minimally invasive investigational tools for biomedical research. This was summarized best in the National Institute of Biomedical Imaging and Bioengineering (NIBIB) FY 2006 budget proposal, which stated that:

> Recent technological advances have revolutionized the diagnosis and treatment of disease and provide unprecedented opportunities for furthering understanding of biological processes … the fields of biomedical imaging and bioengineering are expanding rapidly from the detection, diagnosis and treatment of diseases and disabilities at the level of tissues and organs to the analysis of structure and function at the molecular and genetic levels.
>
> (NIBIB, 2005)

The significance attributed to continued advancements in imaging technology can be appreciated in the NIBIB's request for $299,808,000 to fund the research conducted and supported by its programs.

This section focuses on the planning and design of imaging facilities. A number of technological advancements in recent years have led to the development and availability of smaller and more portable self-contained imaging systems that can be used for rodent imaging procedures. Typically, there are not special or unique facility construction requirements for the portable self-contained imaging units. Klaunberg and Lizak (2004) provide a detailed description for setting up a small-animal imaging facility. Additionally, Pirko *et al.* (2005) provide an overview on how to establish a small animal facility for CNS imaging. Considerations applicable to larger imaging equipment that requires provision of special or unique construction features (i.e., X-ray, MRI, CAT and PET) are also covered.

A. X-ray

Traditional film X-ray imaging is becoming obsolete in the biomedical research environment, as the use of digital X-rays provide an easier, more useful and versatile method for obtaining images utilized in animal research. The design of the facility remains the same whether utilizing processed film or digitized X-rays, with the exception that with digital X-rays a film-processing room is no longer necessary (Figure 19-18).

This can save the institution small but nonetheless valuable space, which can be utilized in other ways. The process for obtaining digital X-rays is also simpler, and does not require the added expense and time to recover the silver nitrate utilized in the developing process. Both processes (film and digital) utilize the same equipment to create the exposure; however, collecting the exposure is where the true difference lies. Film-processed X-rays require the images to be developed in a processing darkroom, whereas digital X-rays are collected on a cassette which can then be downloaded onto a computer or file server. Locating the images on a file server allows several persons access to them, and the images may be viewed at any location that has access to the file server.

Large X-ray imaging equipment consists of a table with a columinator on a tube-stand, a generator cabinet, a console and a high-voltage transformer. The tube-stand has vertical and horizontal tracks that allow the technician to change the orientation of the columinator (which delivers the radiation) to the film plane beneath the tabletop. The generator is fed from the console, which is considered to be the "brains" of the unit, and controls the time and amount of exposure to radiation. Smaller X-ray units incorporate the console and generator into the tabletop, thereby reducing the amount of space that must be dedicated to the process. The transformer converts the standard voltage provided to the tube into X-ray radiation.

There is no stray radiation in the room when the X-ray unit is not in use. X-rays (high-energy electromagnetic radiation produced by the collision of a beam of electrons with a metal target inside an X-ray tube) are created upon activation of the X-ray unit, and therefore appropriate safety precautions must be observed. Limited exposure does not present the safety risks associated with repeated or continual exposure that must be monitored. The NRC regulates the use of radioactive materials and dose limits for personnel working with radiation and for members of the public (NRC, 10 CFR Part 20). Ionizing radiation includes radiation such as alpha and beta particles and X-rays and gamma rays, which have enough energy to knock electrons out of atoms and produce ions. Standard X-rays, CT, PET and SPECT expose study subjects to ionizing radiation. The dose of radiation to personnel can be assessed by a combination of external monitoring by instrumentation, individual monitoring by dosimetry, bioassays of internally deposited radionucludes, or calculations based on exposure conditions and radiation-source characteristics. Personal dosimetry is used to measure the dose from external radiation sources. Dosimetry body badges and finger rings are commonly used to measure personnel exposure on an ongoing basis, for example at monthly intervals.

When designing the layout of the X-ray room, it is important to evaluate the direction of the X-ray beam and the types of spaces surrounding the room where the machine will be located. Radiation travels in a straight line, and scatters when it encounters substances of various radiopacities. The penetrability and "hardness" of X-rays increases with the voltage applied to the X-ray tube. Radiolucent materials such as gypsum board, concrete or earth permit the passage of X-rays, but also afford some resistance – i.e., absorption of radiation. Location of the X-ray machine at an exterior wall where pedestrian traffic is restricted should be considered. In addition, an earthen barrier provides excellent shielding, making basements an excellent choice. Generally, in stud and gypsum board construction, the addition of a lead sheet as thin as 1/16″ to 1/32″ installed at the surface of the wall studs will provide adequate protection for persons outside the room, but this also increases the cost of construction when an exterior wall or basement location is prohibitive. Typically, the lead lining is installed to 7 feet above the finished floor at the wall that is directly in line with the exposure beam, and two layers of gypsum board at the balance of the room. Alternatively, standard CMU construction may inherently provide adequate shielding. A qualified radiological health physicist trained in calculating radiation exposure potentials should be consulted to determine the requirements and the appropriate thickness of lead, or to verify that CMU is adequate for shielding of adjacent spaces. The physicist will provide a report containing the shielding requirements to the architect for inclusion in the room design, and will take the room layout into consideration. Provisions must be made to allow the X-ray technician a view of the X-ray table while at the console and still be protected from radiation during exposures. This can be achieved by providing a control room with a viewing window or by utilizing a simple movable lead-lined shield obtained from the manufacturer. Codes require that a carefully placed emergency power shut-off be located within arm's reach of the control console in case of an adverse incident. Most X-ray equipment suppliers are also capable of providing design services. This can be especially useful when retrofitting an existing facility.

As further development occurs and a wider range of products are offered, many institutions find that smaller portable self-contained digital X-ray units satisfactorily meet their research needs, especially when working with rodents (e.g., Rad Source Technologies, Inc., Boca Raton, FL; www.radsource.com). This combines an ease of use and appropriateness for small-animal imaging studies. Since these units are internally shielded and portable, they have no special requirements other than what is generally provided in a facility – which is adequate standard voltage electrical outlets in ample supply for the X-ray unit itself and for all associated peripheral equipment such as computers.

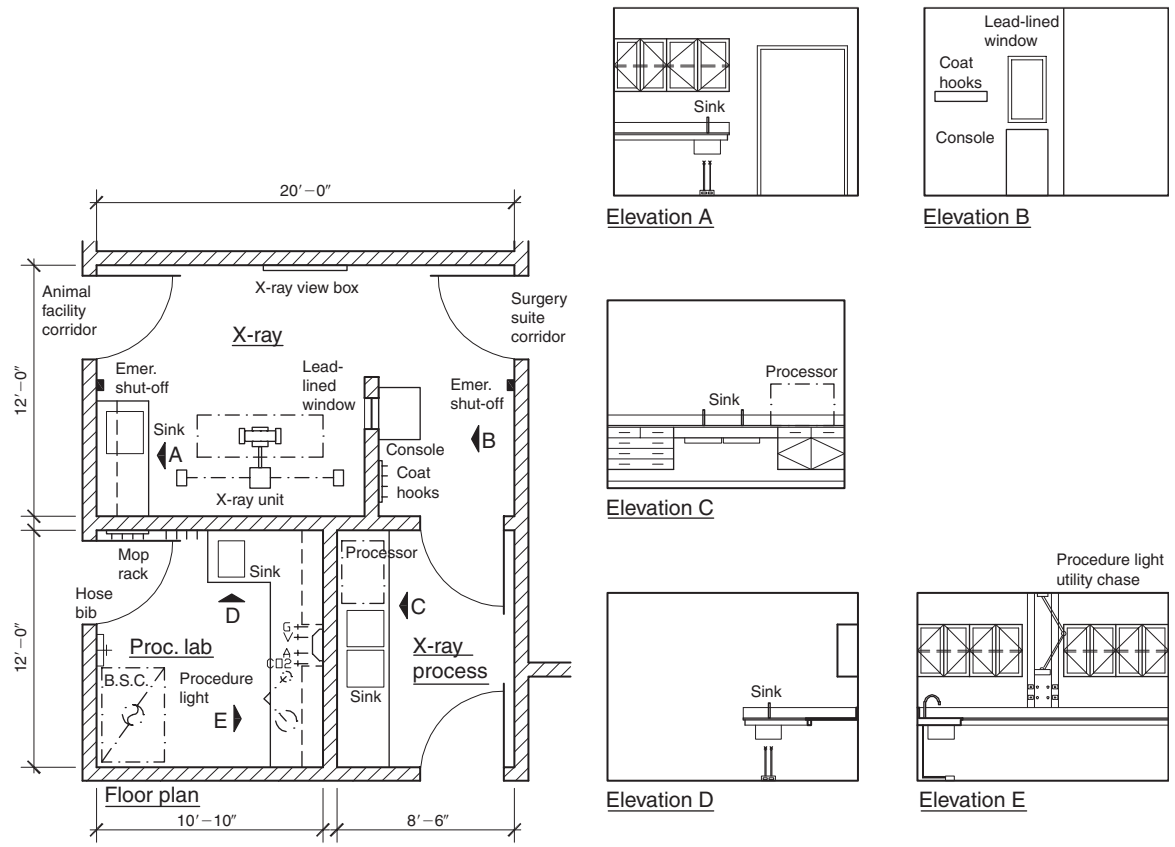


Fig. 19-18 X-ray room and X-ray processing room.

BOX 19-9

FIGURE 19-18: TEXT SUPPORT

X-ray – Room Needs

Room description: room to locate X-ray and fluoroscopic equipment and obtain images to support surgery and/or non-surgery procedures.

Adjacencies: To support surgery procedures, the X-ray suite should be located within or directly adjacent to the surgery suite. When located within the surgery suite dual access should be provided from the animal facility corridor and surgery suite corridor to minimize non-essential traffic through the surgery suite. Direct access to the X-ray processing room and the control room, if provided, should be provided from within the X-ray room. As technology is developing, X-ray imaging is moving from film-based images to digital-based images, which eliminates the need for the X-ray processing room. It is important to confirm and verify the ability to meet all federal, state and local building codes prior to finalizing X-ray equipment location and construction.

Fixed Equipment

X-ray unit: consisting of table, tube stand, generator and console.

Ceiling-mounted horizontal tracks: these require additional support from the structure above to eliminate drift and movement.

X-ray view boxes: to review images for diagnostic use and confirm clarity.

Movable equipment

Animal transport cart: for moving the animal to and from the surgery suite or animal holding room.

BOX 19-9

CONTINUED

Work surfaces

Work surface: there must be adequate standing-height workspace for laying out supplies, instruments, equipment and materials for use in the X-ray room.

Accessories

Coat hooks
Marker board
Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD).

Doors

There should be one each to animal facility and surgery suite corridors, 3′8″ min to 4′0″ wide by 7′0″ high. Doors should be interlocked with the "in use" light in the corridor above the door. Door to X-ray processing room can be 3′0″ min. wide by 7′0″ high if utilized for processing film only. Controlled access to this room from the animal facility and from this room to the surgery suite should be considered.

Windows

There must be a lead-lined window between control room and X-ray table. Visibility of X-ray table from the console must be provided at all times when the X-ray unit is in use.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted.
Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents and disinfectants. Adequate protection from the X-ray radiation emitted by the X-ray unit must be considered for the spaces that adjoin the X-ray room. All shielding requirements should be determined or confirmed by a radiological health physicist, who will take into consideration equipment placement, weekly projected workloads, and materials used for construction. The physicist will determine the required thickness of concrete or concrete masonry unit walls or, if gypsum board walls are utilized, the amount of lead shielding that may be required at the wall directly in line with the X-ray beam. Frequently, only the wall in line with the X-ray beam will require lead shielding, and the balance of the walls are provided with a double layer of gypsum board.
Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sinks should be considered.

Electrical

Lighting: general-purpose lighting should be provided at 50–70 foot-candles as measured at 3′0″ above the floor. Dimmable lights should be provided, allowing the lighting levels to be reduced during the time of exposure yet adequate to align the image-capture film or digital canister with the X-ray beam. It is recommended that the doors be interlocked with an "in use" light located outside of the room (ASHRAE/IESNA, 2004).
Power: general-purpose electrical outlets should be provided in the room. Specific power requirements for the X-ray unit vary with the size of the unit. Smaller units typically require 220-V, 100-A single-phase power, whereas larger units may require 220-V, three-phase power. All power requirements must be verified with the manufacturer. Emergency shut-off of the X-ray unit must be accessible within an arm's reach when standing at the console unit.
Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be

(*Continued*)

BOX 19-9

CONTINUED

located in the room and will be connected to a file server. Provisions for wireless computer access are becoming more prevalent, and if these are provided in the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least six changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite and animal facility should be negative.

X-ray Processing – Room Needs

Room description: used for processing of film X-ray images.

Adjacencies: locate adjacent to and with direct access from X-ray imaging room. Room should be located with convenient access to the surgery suite. This room may be eliminated from the program if digital based images are utilized by the facility. This room may also be utilized to store portable, self-contained imaging equipment.

Fixed Equipment

X-ray view boxes: to review images and confirm clarity.

Movable Equipment

X-ray processor: either floor-mounted or counter-top type X-ray film processor, if film-based imaging is utilized.

Portable X-ray unit: if room is utilized to store portable, self-contained imaging equipment.

Work Surfaces and Storage

Work surface: there must be adequate standing-height workspace for laying out equipment, supplies, and materials for use in film processing.

Storage: there should be floor-mounted casework for storage of processing supplies.

Accessories

Coat hooks.

Doors

There should be one door each into the X-ray imaging room and animal facility corridor, 3′0″ min. wide by 7′0″ high if utilized for processing film only; if utilized for equipment storage, doors should be 3′8″ min. wide by 7′0″ high to facilitate equipment movement. Doors should be interlocked with the "red light" switch and "in use" light in the corridor above the door. A rotating light-tight X-ray room door should be provided in facilities where multiple people utilize the room, to prevent accidental exposure of X-ray film. A light-tight swing door may be adequate for use in smaller programs where space is limited.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted; capable of withstanding cleaning with detergents and disinfectants.

Walls: Smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners.

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: one double sink with shallow bowls and hot and cold water for image-developing. Drainage requirements for processing unit must be verified. For units that utilize silver nitrate, there must be a sink or cup sink located at the wall or work surface. The waste should be directed to a dedicated collection container for recovery of the captured silver nitrate.

Electrical

Lighting: there should be general-purpose lighting levels of 50–70 foot-candles min. when measured at 3′0″ above the floor. There should be supplemental "red light" room illumination for use during the developing process if X-ray negatives are to be developed in the

BOX 19-9

CONTINUED

room. It is recommended that the red-light light-switch be located remote from the general room lighting switch and interlocked with the door, and an "in use" light located outside of the room to prevent accidental exposure of X-ray film (ASHRAE/IESNA, 2004).

Power: there must be a sufficient number of general-purpose duplex outlets for equipment that it is anticipated may be utilized in the room.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety, as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

HVAC: temperature and humidity should be consistent with animal holding room provisions. At least 10 changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite and animal facility should be negative (ASHRAE, 2003).

B. Magnetic Resonance Imaging (MRI)

The design of an MRI facility can be very complex. The MRI unit is comprised of three major components; a magnet, a control console and a computer. Magnetic fields and radio waves are used to produce high-quality 2-D or 3-D images without administering radioactive tracers (Mathias, 1996). It is essential to carefully coordinate design activities between the equipment manufacturers, those who will utilize and service the facility, and the architects and engineers who will facilitate the planning (Figure 19-19). The architect and engineers are responsible for designing the necessary layout of the equipment, as well as ensuring that the mechanical, plumbing and electrical services required for the equipment are adequate. Adherence to local, state and federal codes must be confirmed.

The magnetic field generated by an MRI unit can be very dangerous to humans with medical conditions (such as pacemakers), and can damage the peripheral equipment utilized by the MRI unit and equipment that is located in surrounding areas within the MRI unit's field of influence, expressed as levels of gauss (the unit of magnetic flux density). In addition, the magnet can be influenced by stationary metal structural components of the building, such as beams, columns and metal stud walls; by large moving components such as elevators, hand trucks and vehicles; and by outside interference of radio and TV frequencies, paging systems, telephones, electrical power lines and transformers (Barrington Medical Imaging, LLC; Varian, Inc.). These items can influence the homogeneous field which is required for optimal, consistent and accurate information provided by the MRI unit. For this reason, site selection is a primary factor to consider when planning for MRI facilities, and the selected location should be confirmed with the equipment manufacturer before plans are finalized. MRI units which are not equipped with internal shielding (or are not termed "self contained") require passive shielding, which dictates a requirement for more space to isolate the magnetic field from the surrounding environment, both horizontally and vertically, or that shielding be provided as a component of construction to contain the magnetic field and eliminate outside interference. Passive shielding is achieved by installing strategically placed ferromagnetic plates around the magnet, thereby reducing the static magnetic field. Passive shielding may be provided as a component of construction to contain the magnetic field and eliminate outside interference;

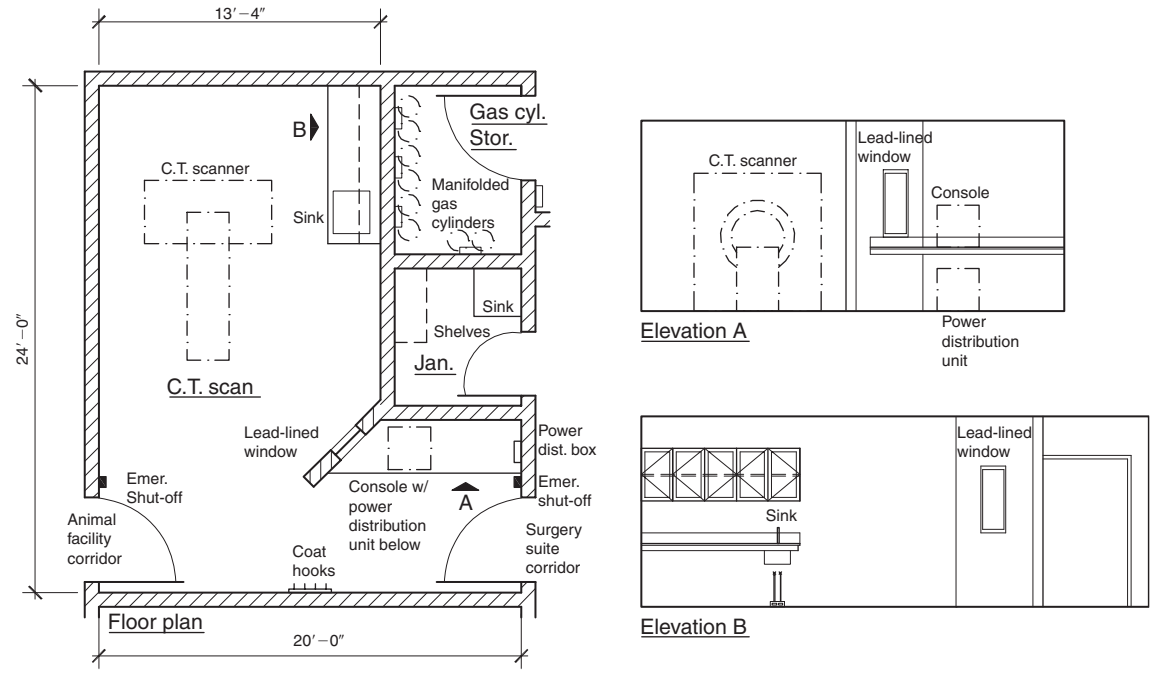


Fig. 19-19 Computed tomography (CT) room.

however, this requires careful analysis by a trained professional. Self-contained or internally shielded units are more costly but reduce or contain the magnetic field within a smaller circumference, allowing for more flexibility in placement of the MRI unit within the facility.

The strength of the magnet in conjunction with the bore size will determine the size of the "stray particle field" and level of gauss at any specified distance from the center of the core magnet of an unshielded unit. This information is obtained from the manufacturer, as it is specific to each individual unit and is paramount in the design of a safe facility. Regardless of whether a unit is internally shielded or not, it is necessary that the 5-gauss circumference be located within the room or in an area where it is not anticipated that a person would have casual contact with the unit's field of influence, such as in a subterranean and/or heavily landscaped exterior area. In order for the MRI unit to function properly, it is necessary for the console to be located in an area not to exceed the 10-gauss line, and all computers must be located outside the 1-gauss line. Frequently an adjoining room with a view window is provided for the operator and peripheral equipment, to eliminate risks of exposure to the magnet's field of influence.

There are other areas of hazard concern. One is the potential for quenching the magnet, resulting in the release of hydrogen into the room, which could deplete the room of oxygen. This potential hazard can be addressed by providing direct exhaust to the outside, or by increasing the room ceiling height to capture the hydrogen as it is expelled and thereby maintain safe oxygen levels within the room. Liquid nitrogen, also necessary for the functioning of an MRI unit, poses another potential hazard, as the extreme cold of liquid nitrogen poses a serious frostbite hazard and the high volume expansion ratio of boiling nitrogen (boiling point −195.8°C or −320.4°F) can displace the air in the room, making breathing difficult. When it boils, each liter of liquid nitrogen will expand to nearly 700 liters of nitrogen gas. Liquid nitrogen can also cause serious damage to surrounding equipment or materials. Routine delivery and movement of hydrogen and nitrogen dewars to the MRI unit should be safe, easy, and obstacle-free. Extreme caution must be exercised, and adequate clearances around the equipment must be provided for personnel in addition to provisions for safe ceiling heights. These factors help to determine start-up and servicing requirements of the MRI unit, for which the unit's manufacturer will provide. In addition, provisions for emergency evacuation routes must be carefully planned.

The initial planning for an MRI facility should include consideration of access and movement of the equipment into the facility, which is generally the responsibility of the end-user. MRI units can weigh as much as 5 tons, and can be larger than typical door or corridor openings in a research facility. Adequate clearances must be available for movement of the unit in an upright position from its delivery point to the facility, and the structural capability of the building must be sufficient to carry the load along the entire path of travel. For this reason, it is not unusual that a separate building is often provided for the MRI unit, or that the MRI unit is located on the ground floor at an exterior wall. Operable roofs allow cranes to maneuver the MRI unit, or removable walls can

be installed to provide adequate openings for large, moving equipment.

Vibration will likely be more of an issue as advancements in MRI unit development becomes more refined. Building-movement limitations must be confirmed with the manufacturer. The magnet itself can have a long useful life. Refinement and development of the console occurs more rapidly, and it can be replaced while utilizing the same magnet. Computer software to support the MRI and console is developing at a fairly rapid pace, and can be anticipated to change as research advances and the uses of the MRI increase, while utilizing the same magnet and console. Due to the long life of the MRI unit and the initial cost of the equipment, animal research facilities frequently obtain used equipment from other sources, such as medical facilities, who upgrade their equipment with more advanced versions. It is for this reason that the design of the facility not only be considered for state-of-the-art equipment but also for equipment that may be considered obsolete by other facilities. The MRI unit is sensitive to temperature and humidity changes, and both must be carefully controlled. Frequently, room-specific mechanical units are provided to obtain these tight controls, as it can become a burden or introduces unnecessary costs for the overall building system (Barrington Medical Imaging, LLC; Varian, Inc.; GE Medical Systems; Siemens Medical Solutions USA).

BOX 19-10

FIGURE 19-19: TEXT SUPPORT

Magnetic Resonance Imaging (MRI) – Room Needs

Room description: room to locate MRI equipment and obtain images to support surgery and/or non-surgery procedures.

Adjacencies: to support surgery procedures, the MRI room should be located within or directly adjacent to the surgery suite. When located within the surgery suite, dual access should be provided from the animal facility corridor and surgery suite corridor to minimize non-essential traffic through the surgery suite. Site selection should consider a location where the magnet provides the least interference with the building it occupies. Careful coordination of the level of gauss at specific distances from the equipment, which is unique to the equipment selected, helps in determining an appropriate location. It is recommended that this room be located adjacent to areas that are not frequently occupied or, most ideally, at an exterior wall or in a basement, as earth provides excellent shielding. It is important to confirm and verify the ability to meet all federal, state and local building codes prior to finalizing MRI equipment location and construction.

Fixed Equipment

MRI imaging equipment: imaging magnet, console, power supply cabinet, RF cabinet, and controller.

Movable Equipment

Computer workstation: for the MRI host computer.
Gas dewers: liquid nitrogen (LN_2) and helium (H_2) dewers to support the MRI equipment. Dewer size is determined by the anticipated consumption of the MRI unit and frequency of delivery.

Accessories

Marker board
Cleaning implements holding rack (“mop rack”) (Life Science Products, Inc., Chestertown, MD)
Coat hooks
Peg board, with wood or plastic pegs for storage of cryogenic equipment used for routine maintenance and handling.

Doors

There should be one 3′8″ min. wide by 7′0″ high door each to the animal facility and surgical suite. The doors should be interlocked with the “in use” light in the corridor above the door. Controlled access to this room from the animal facility and from this room to the surgery suite should be considered.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted. It is recommended that electrostatic dissipative (ESD) flooring material be provided in the area directly around the magnetic. The extent of the ESD flooring is dependent on the layout of the room and location of peripheral equipment.
Walls: Smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and

(*Continued*)

BOX 19-10

CONTINUED

unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Floors should be capable of withstanding cleaning with detergents and disinfectants.

Ceiling: Smooth, moisture-resistant, and free of joints and imperfect junctions. Capable of withstanding cleaning with detergents and disinfectants.

Special Construction

Adequate ceiling height must be provided directly above the MRI unit to allow the insertion of the liquid helium transfer tube into the magnet. Ceiling height requirements must be confirmed with the manufacturer, but frequently 10–12 feet is provided. Depending on the unit selected, the room may need additional radiofrequency (RF) shielding. Requirements for RF shielding should be confirmed with the manufacturer.

Plumbing

Chilled water may be required, depending on the unit selected. This may be accomplished by connecting the equipment to the building chilled-water recirculating loop, or by providing a dedicated chiller unit that is connected to and supplies the MRI equipment. The requirement for chilled water must be verified with the manufacturer, and is specific to the unit selected.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Dimmable lights should be provided, allowing the lighting levels to be reduced during the time of exposure yet adequate to align the subject with the equipment. Incandescent lighting is preferred; if fluorescent light fixtures and dimmer switches are utilized then they must be carefully coordinated to reduce possible RF interference of the ballasts with the MRI unit. It is recommended that the doors be interlocked with an "in use" light located outside of the room (ASHRAE/IESNA, 2004).

Power: there must be standard voltage general-purpose duplex outlets in the room, as required, in addition to dedicated duplex outlets for test equipment, the water-cooling unit and the host computer. Single- or three-phase power with voltage of 220 V or higher is commonly required for the power supply cabinet, RF cabinet, console and controller. A dedicated circuit-breaker with lock-out capabilities and an emergency shut-off should be installed in the room for local control of the power that is supplied for all the MRI equipment. All electrical requirements should be confirmed and coordinated with the manufacturer.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. In addition, a surge protector or power regulator should be considered if the power to the facility experiences unacceptable line voltage fluctuations. An uninterrupted power supply (UPS) should be provided if a facility experiences frequent power outages or the change over time from general building power to emergency power is unacceptable while experiencing a building-wide power outage. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

For optimal performance, the room temperature around the magnet should remain stable. Standard room temperatures controlled within ±2°F should be maintained. The addition of a supplemental, dedicated air chiller within the room may be required. At least six changes of 100% outside air should be provided, with adequate provisions to ventilate displaced liquid helium gas during a quench. Directional air flow in relationship to the adjoining surgery suite and animal facility should be negative (ASHRAE, 2003).

C. Computer-Assisted Tomography (CT)

Computer tomography (CT), also known as computerized axial tomography (CAT), has become widely used in animal research. Essentially, CT is a three-dimensional X-ray technique, which is sensitive to the X-ray absorption of the tissue (Balaban and Hampshire, 2001). CT technology uses special X-ray equipment to obtain anatomical data from different angles around the body simultaneously, and then uses computer processing of that data to show a detailed high-resolution cross-section of bones, tissues and organs. The equipment utilized to obtain a CAT scan image includes a rotating gantry, an X-ray tube mounted inside the gantry, a console, and multiple computers to control the unit and capture and assemble the images (Figure 19-20). CAT scans utilize the same principles as traditional X-ray imaging, but differ in the outcome or results. Traditional X-rays provide a single 2-D exposure, whereas CAT scans provide multiple images that can be assembled on a computer into a 3-D model clearly showing small bones and many types of tissue, including organs, soft tissues and blood vessels. Due to the fact that multiple images are gathered, the amount of X-ray exposure required for CT imaging is increased. CT technology is quickly changing and developing, which prohibits thorough coverage here of all the options currently available (Barrington Medical Imaging, LLC; GE Medical Systems; Siemens Medical Solutions USA, Inc).

CAT scanning began with a simple machine that produced a single 2-D cross-sectional image known as a "slice." This technology quickly developed into multi-slice units, which provide more images and the ability to assemble 3-D models. The speed at which the unit can capture and process slices, as well as the number of slices the unit will capture, continues to increase, with 4-, 16- and 64-slice units commonly in use, greatly enhancing the versatility and usefulness of this technology. The number of slices that a unit is capable of capturing is directly proportional to the number of images captured per second. As the number of detectors increases, both the speed of the scanning and the resolution of the images increase. Further developments have resulted in the spiral (helical) CT, which increases the accuracy of the images because the unit captures continuous spiracle data and therefore gaps or image interruptions are decreased if not eliminated. In addition, higher-quality images are acquired with less radiation exposure. Electron-beam CT scanning is another type of imaging that obtains images at a much faster rate than standard CT scanners, allowing clearer and more accurate images of the body, such as the heart and arteries while in motion. Although electron-beam imaging units are currently the most recent development, this technology is also sure to change and advance over time. Even further developments have allowed the combination of computer tomography and positron emission tomography (PET), which combine anatomical and functional imaging within a single unit, thus providing even greater possibilities and usefulness in research. Even more useful for animal research is the development of CT scanners that are portable and internally shielded, which increases the versatility of the technology and reduces construction requirements that must be adhered to for standard CT units.

The design of a CT suite must consider the requirements of both an X-ray imaging suite and an MRI room as outlined in the sections above (Barrington Medical Imaging, LLC). CT imaging utilizes X-ray beams, and therefore all requirements for X-ray shielding must be determined and provided. Both CT and MRI imaging units can be quite large and extremely heavy, and all considerations for structural requirements and installation path of travel, as outlined in the MRI section above, are a must. If a combined CT/PET unit is selected, then the additional requirements for a "hot lab" (see the PET section below) must be added to the functional program for facility design.

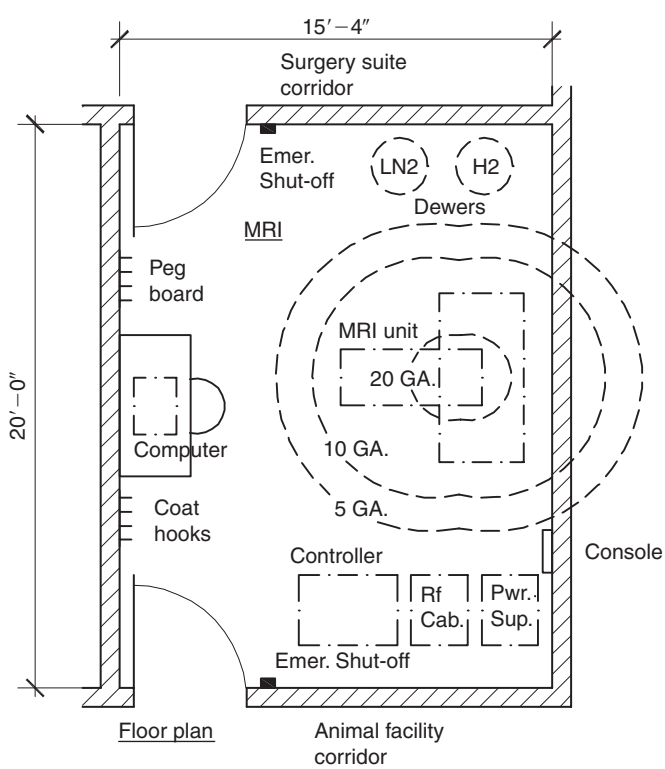


Fig. 19-20 Magnetic resonance imaging (MRI) room.

BOX 19-11

FIGURE 19-20: TEXT SUPPORT

Computed Tomography (CT) – Room Needs

Room description: room to locate CT equipment and obtain images to support surgery and/or non-surgery procedures.

Adjacencies: to support surgery procedures, the CT room should be located within or directly adjacent to the surgery suite. When located within the surgery suite, dual access should be provided from the animal facility corridor and surgery suite corridor to minimize non-essential traffic through the surgery suite. It is important to confirm and verify the ability to meet all federal, state and local building codes prior to finalizing CT equipment location and construction.

Fixed Equipment

CT equipment: scanning gantry, table and power distribution unit (PDU).

Movable Equipment

Support equipment for the CT scanner: operator's console and any selected optional equipment.

Work Surfaces and Storage

Work surface: there must be adequate standing-height workspace for laying out supplies, instruments, equipment and materials for use in the CT room.

Accessories

Marker board
Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD)
Coat hooks.

Doors

There should be one 3′8″ min. wide by 7′0″ high door each to the animal facility and surgical suite. Doors should be interlocked with the "in use" light in the corridor above the door. Controlled access to this room from the animal facility and from this room to the surgery suite should be considered.

Windows

There must be a lead-lined window between the control room and CT scanning table. Visibility of the CT table must be provided at all times when the CT unit is in use.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted. The CT gantry and table must not be mounted on top of floor finishes which may settle or creep over time due to the excessive weight of the equipment. It is recommended that the gantry and table be mounted directly onto the concrete substrate or onto a sheet of metal 1/2″ thick. Electrostatic dissipative flooring material should be considered. CT units can be sensitive to vibration; vibration requirements for the CT unit should be confirmed with the manufacturer.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Adequate protection from the X-ray radiation emitted by the CT unit must be considered for the spaces that adjoin the CT scanner room. All shielding requirements should be determined or confirmed by a radiological health physicist, who will take into consideration equipment placement, weekly projected workloads, and materials used for construction. The physicist will determine the required thickness of concrete or concrete masonry unit walls or if gypsum board walls are utilized the amount of lead shielding that may be required.

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the room. Hands-free operation of the sink should be considered.

Chilled water may be required, depending on the unit selected. This may be accomplished by connecting the equipment to the building chilled-water recirculating loop or by providing a dedicated chiller unit that is connected to and supplies the CT equipment. The requirement for chilled water must be verified with the manufacturer, and is specific to the unit selected.

BOX 19-11

CONTINUED

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Dimmable lights should be provide, allowing the lighting levels to be reduced during the time of exposure yet adequate to align the subject with the equipment. It is recommended that the doors be interlocked with an "in use" light located outside of the room (ASHRAE/IESNA, 2004).

Power: there must be standard voltage general-purpose duplex outlets in the room, as required, in addition to dedicated duplex outlets for all peripheral equipments. Three-phase power with voltage of 220 V and higher is generally required for the power distribution box (PDB) which supplies the power distribution unit (PDU). A dedicated circuit-breaker with lock-out capabilities and an emergency shut-off should be installed in the room within arm's reach of the controller for local control of the power that is supplied for all the CT equipment. In addition, an emergency shut-off should be installed at each exit door. All electrical requirements should be confirmed and coordinated with the manufacturer.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. In addition, a surge protector or power regulator should be considered if the power to the facility experiences unacceptable line-voltage fluctuations. An uninterrupted power supply (UPS) should be provided if a facility experiences frequent power outages or the change over time from general building power to emergency power is unacceptable while experiencing a building-wide power outage. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. One telephone outlet should be provided regardless of the computer needs. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

The room temperature in the CT scanning and console room should remain constant even during weekends and holidays. Standard room temperatures controlled within ±2°F should be maintained. The addition of a supplemental, dedicated air chiller within the room may be required. At least six changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite and animal facility should be negative (ASHRAE, 2003).

D. Positron Emission Tomography (PET)

Positron emission tomography (PET) scanning is a type of nuclear medicine technology that measures the metabolic activity of cells, making it very useful for studying the functions of organs such as the heart and brain. PET scanning studies are actually a combination of nuclear medicine and biochemical analysis, which utilizes tracer chemicals labeled with special radiological pharmaceuticals to record functions and abnormalities in organs as the tracers are metabolized. PET measures emissions from the radioactive tracers that have been administered into the bloodstream, and uses the data to produce 2-D or 3-D images of tracer distribution throughout the body (Mathias, 1996). The tracer and radioisotopes are selected according to the specific function of the organs to be observed and the length of the study. Metabolic activity is collected by the PET scanner and interpreted by the computers, which then create a visual image. The acquisition time for imaging is longer for a PET scan than for an X-ray, a CT scan or an MRI scan, because the scanner collects dynamic data on metabolism rather than providing static images.

A PET system consists of a circular gantry, the detector assembly, lasers used to position the subject to be scanned, and the computer systems that interpret the information and create

the images from the scanners data. The PET suite should allow for a control room, space for animal preparation procedures (e.g., anesthesia and injections), a radiopharmaceutical laboratory (a "hot lab") and a utility room (Figure 19-21). The PET control room houses the multiple image collecting computers as well as the uninterrupted power supply (UPS). The PET system requires sensitive temperature control, and the utility room contains the building's supplemental cooling system required to maintain the required temperatures. Both the hot lab and PET scanner room require radiation shielding, which is frequently achieved by installing lead at the wall stud surfaces. A qualified radiological health physicist should be consulted to determine all shielding requirements. The PET system manufacturer and type of unit to be used will dictate the size of not only the scanner room but also the supporting control and utility rooms. Frequently facilities are renovated to accommodate the PET system, and irregular spaces may be able to be utilized. Careful coordination between the end-users, the architect, equipment manufacturer and engineers must be part of the planning process to ensure that system and facility requirements can be achieved for the system purchased.

As with other imaging modalities, PET scanning abilities and advances are rapidly changing the capabilities and possibilities of scientific research approaches. Small, portable PET scanning units are now available which are self-contained, thereby increasing the flexibility of the unit's location within the facility and also reducing the facility's construction requirements. Further developments have introduced PET/CT scanners. By combining the capabilities of a CT scanner to collect metabolic activity with a PET scanner, images are created that anatomically locate the sources of the PET data, greatly enhancing the accuracy of image alignment and thereby combining the best of both scanning modalities with a single unit.

The design of a PET/CT suite must consider the shielding requirements of both the X-ray and CT imaging rooms, due to the use of X-ray beams. MRI-room structural and installation path-of-travel requirements must also be considered, because PET and CT units are generally extremely heavy and larger than standard doors along the installation access route (Barrington Medical Imaging, LLC; GE Medical Systems; Siemens Medical Solutions USA, Inc).

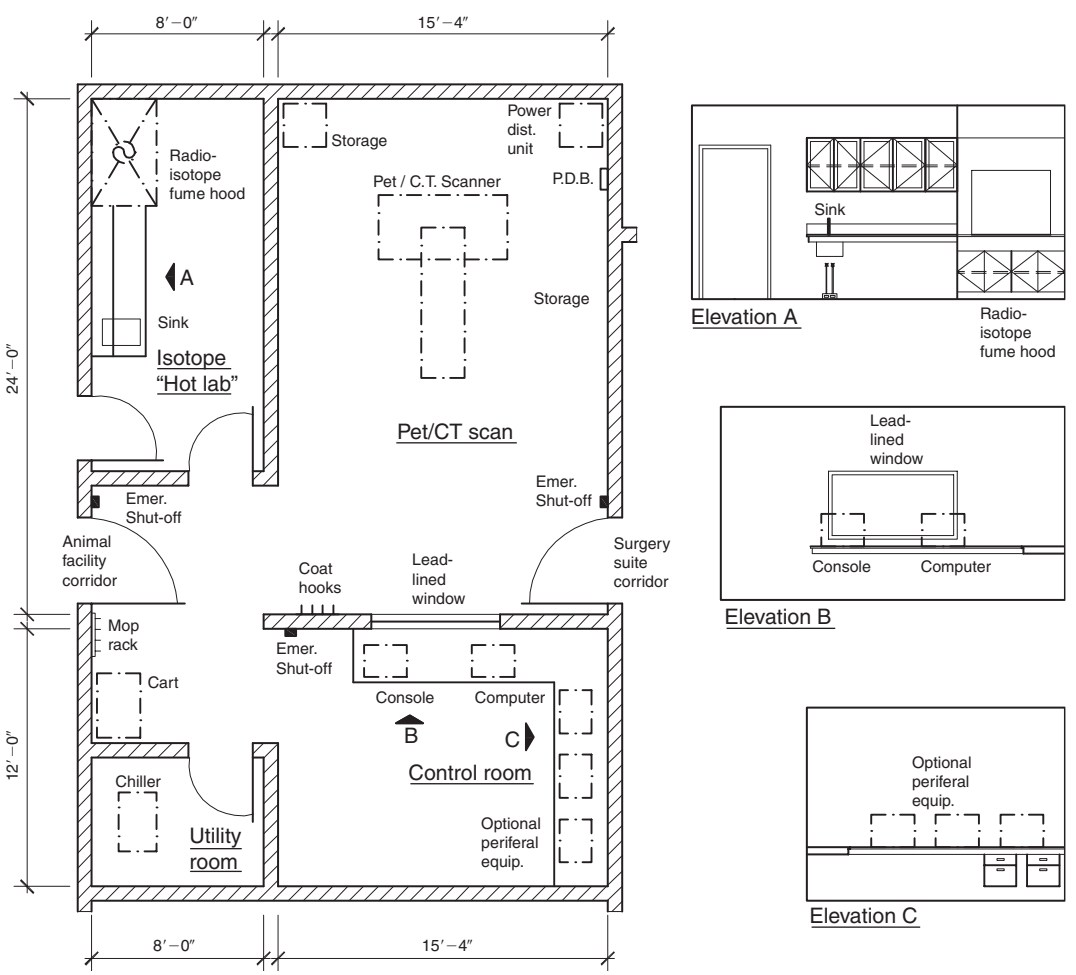


Fig. 19-21 Positron emission tomography/computed tomography (PET/CT) suite.

BOX 19-12

FIGURE 19-21: TEXT SUPPORT

Positron emission Tomography (PET)/ Computed Tomography (CT) – Room Needs

Room description: utilized to locate PET equipment and obtain images to support surgery and/or non-surgery procedures.

Adjacencies: the PET/CT room should be located adjacent to and with direct access to the control room and "hot lab." To support surgery procedures, the PET/CT suite should be located within or directly adjacent to the surgery suite. When located within the surgery suite, dual access should be provided from the animal facility corridor and surgery suite corridor to minimize non-essential traffic through the surgery suite. The associated utility room can be located remote to the PET/CT room as long as maximum distances, as specified by the manufacturer, are not exceeded. It is important to confirm and verify the ability to meet all federal, state and local building codes prior to finalizing MRI equipment location and construction

Fixed Equipment

PET/CT equipment: scanning gantry, table, power distribution unit (PDU) and power distribution box (PDB). The associated "hot lab" is to be provided with a radio-isotope fume hood.

Movable Equipment

Support equipment for the PET/CT scanner: operator's console, host computer, storage cabinet, UPS and any selected optional equipment.

Work Surfaces and Storage

Work surface: there should be adequate standing-height workspace for laying out supplies, instruments, equipment and materials for use in the PET/CT "hot lab," and adequate sitting-height workspace for all peripheral equipment located in the control room.

Storage: adequate storage space should be provided for various supplies. The manufacturer provides a storage cabinet for storage of sensitive equipment and supplies associated with the PET/CT unit.

Accessories

Marker board

Cleaning implements holding rack ("mop rack") (Life Science Products, Inc., Chestertown, MD)

Coat hooks.

Doors

There should be one 3′8″ min. wide by 7′0″ high door each to the animal facility and surgical suite. Door should be interlocked with the "in use" light in the corridor above the door. Controlled access to this room from the animal facility and from this room to the surgery suite should be considered.

Finishes

Floor: monolithic, moisture-resistant, non-absorbent, impact-resistant, relatively smooth, and resistant to water and cleaning agents. Capable of supporting racks and equipment without becoming gouged, cracked or pitted. The PET/CT gantry and table must not be mounted on top of floor finishes which may settle or creep over time due to the excessive weight of the equipment. It is recommended that the gantry and table be mounted directly onto the concrete substrate or onto a sheet of metal 1/2″ thick. Electrostatic dissipative flooring material should be considered. PET/CT units can be sensitive to vibration; vibration requirements for the PET/CT unit should be confirmed with the manufacturer.

Walls: smooth, moisture-resistant, non-absorbent and resistant to damage from impact. Free of joints and unsealed penetrations or imperfect junctions with doors, ceilings, floors and corners. Adequate protection from the X-ray radiation emitted by the CT unit must be considered for the spaces that adjoin the CT scanner room. All shielding requirements should be determined or confirmed by a radiological health physicist, who will take into consideration equipment placement, weekly projected workloads, and materials used for construction. The physicist will determine the required thickness of concrete or concrete masonry unit walls or, if gypsum board walls are utilized, the amount of lead shielding that may be required.

Ceiling: smooth, moisture-resistant, and free of joints and imperfect junctions; capable of withstanding cleaning with detergents and disinfectants.

Plumbing

Sinks: one sink, with hot and cold water, should be provided for hand-washing and general cleaning of supplies within the "hot lab." Hands-free operation of the sink should be considered.

(*Continued*)

BOX 19-12

CONTINUED

Chilled water may be required, depending on the unit selected. This may be accomplished by connecting the equipment to the building chilled-water recirculating loop or by providing a dedicated chiller unit that is connected to and supplies the CT equipment. The requirement for chilled water must be verified with the manufacturer, and is specific to the unit selected.

Electrical

Lighting: there should be general-purpose room lighting at 50–70 foot-candles minimum measured at a level of 3′0″ above the floor. Dimmable lights should be provided, allowing the lighting levels to be reduced during the time of exposure yet adequate to align the subject with the equipment. It is recommended that the doors be interlocked with an "in use" light located outside of the room (ASHRAE/IESNA, 2004).

Power: there must be standard voltage general-purpose duplex outlets in the room, as required, in addition to dedicated duplex outlets for all peripheral equipment. Three-phase power with voltage of 380 V to 480 V is generally required for the power distribution box (PDB) which supplies the power distribution unit (PDU). A dedicated circuit-breaker with lock-out capabilities and an emergency shut-off should be installed in the room within arm's reach of the controller for local control of the power that is supplied for all the PET/CT equipment. In addition, an emergency shut-off should be installed at each exit door. All electrical requirements should be confirmed and coordinated with the manufacturer.

Special power: all essential lighting and equipment should be connected to emergency power in case of power failure during procedures. In addition, a surge protector or power regulator should be considered if the power to the facility experiences unacceptable line-voltage fluctuations. An uninterrupted power supply (UPS) should be provided if a facility experiences frequent power outages or the change over time from general building power to emergency power is unacceptable while experiencing a building-wide power outage. The anticipated duration of temporary power should be calculated based on the facility protocol which would stipulate that the facility is to remain fully functional or only that adequate time is allotted to safely interrupt the procedure without jeopardizing the health and welfare of personnel or animals.

Telecommunications

Telephone, data outlets: one data outlet should be provided for each computer workstation that will be located in the room and connected to a file server. Provisions for wireless computer access terminals are becoming more prevalent, and if these are provided by the facility data outlets can be minimized or omitted. Two telephone outlets should be provided regardless of the computer needs. One telephone line should be dedicated to the equipment, allowing the manufacturer access to the equipment for remote trouble-shooting. Hands-free telephones are desirable.

Intercom/paging speakers: voice contact between those inside and outside of the room is essential for safety as well as a connection to the building paging system, which may be used in times of emergencies (local or building-wide) or in locating individuals within the facility.

Mechanical

The room temperature in the PET/CT scanning and console room should remain constant even during weekends and holidays. Standard room temperatures controlled within ±2°F should be maintained. The addition of a supplemental, dedicated air chiller within the room may be required. At least six changes of 100 percent outside air should be provided. Directional air flow in relationship to the adjoining surgery suite and animal facility should be negative (ASHRAE, 2003).

VIII. RESEARCH EQUIPMENT AND SUPPLY STORAGE

As more research procedures involving animals are conducted inside the central animal facilities, provision for the storage of research equipment and supplies becomes an issue that needs to be addressed. Some investigative groups may have special equipment and supplies that would be required to conduct animal-use procedures in shared areas (e.g., the surgery suite or a procedure laboratory), but storage in those areas would not be appropriate. In some situations a unique apparatus or other equipment may be used on an intermittent basis

(e.g., various mazes, running wheels, animal behavior chambers, etc.). Some required research equipment might only be used during three to four studies per year, which is not uncommon in some contract research organizations that provide a variety of services. Unused equipment and supplies should not be stored in active animal-use areas, as adequate room sanitation can be compromised and particulate contaminants can pose a potential health and safety risk to personnel and study animals. This is especially true if equipment and supplies are allowed to accumulate to the point of cluttering the animal-use space. Institutional Animal Care and Use Committees should monitor these areas to ensure that practices do not become problematic. Assignable dedicated space should be considered for investigative groups to store their equipment and supplies when not being used. Where it is not feasible to transport larger equipment items, provision should be available in dedicated procedure laboratories to keep these items. In such instances, there should be a method to cover and protect items that are not being used. Smaller items can be kept in lockable modular/portable storage cabinets that can be placed in a designated storage area. When needed, the storage cabinets can be transferred to the procedure area where they are needed, and then cleaned and returned to the storage area after the animal-use procedure session has concluded. Figure 19-3f shows such a portable cabinet and transfer dolly (Herman Miller, Inc., Zeeland, Michigan; www.hermanmiller.com).

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B: Species-specific Housing Space

Chapter 20

Rodent Facilities and Caging Systems

Neil S. Lipman

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I. INTRODUCTION

Rodents are, by far, the most commonly used animal models in biomedical research today. Genetically altered mice, especially transgenic and gene targeted lines, as well as inbred and mutant strains, have become the instruments driving biomedical technology and research. Many research institutions are grappling with the task of housing and caring for rapidly expanding rodent populations. The design of new facilities is driven, in part, to accommodate large rodent populations. Biosecurity (defined as all measures taken to detect, prevent, contain and eradicate adventitious infections) is also critical, as infectious agents are well-recognized to perturb the animal's physiology and biologic responses, potentially affecting research results (reviewed in Lipman and Perkins, 2002). In addition, many genetically engineered lines are unique, and may be immunosuppressed and exquisitely sensitive to adventitious pathogens. As a result, barrier housing is often employed for maintaining rodent colonies.

The term *barrier* is used widely in laboratory animal management and operations and has a variety of connotations. Barriers are obstacles that hinder passage or impede an activity. In the context of animal facilities, barriers are special features to prevent infection of the research animals with unwanted infectious agents. Barriers may be special building, equipment or program features that hinder the passage of contaminants into the facility or designated areas. A barrier, both physical and operational, is established around the animals to prevent introduction of unwanted adventitious agents. It is essential to define "barrier" in the context of the facility's design, and also in terms of its operations. It is important to understand and define how animals, personnel and materials will be moved, the housing systems utilized, and the desired animal health status to be maintained.

Because of rodents' small size, barriers can be established at the cage, room, suite and/or facility level. The use of a cage-level barrier has become common practice in research facilities, and has revolutionized the care of rodents. Experience with the rodent isolation cage over many years has substantiated that it can protect rodents from unwanted infectious agents when used in a defined program of animal care. Such programs consist of the following:

1. Isolation cages
2. Sanitation or sterilization of cages and water bottles
3. Storage of sanitized cages and bottles to prevent contamination
4. Use of uncontaminated food and bedding
5. Use of biological safety cabinets, which provide protection to both the animals (product) and personnel, or change stations with HEPA filtered air, which provide animal (product) protection (Figures 20-1, 20-2)
6. Use of forceps and disinfectants following defined procedures when handling animals.

Isolation caging systems may be used alone or be supplemented with facility barriers.

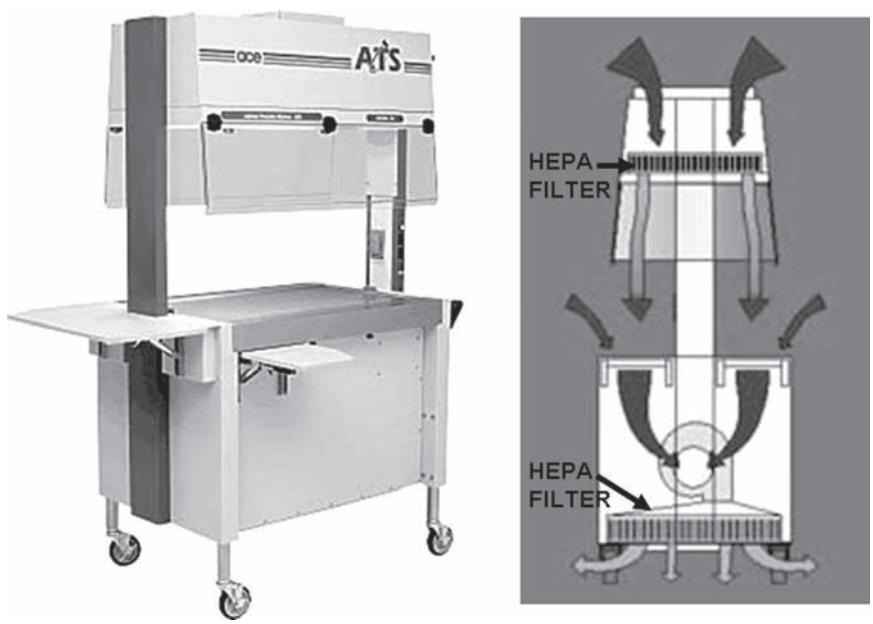


Fig. 20-1 Vertical flow changing station (left). HEPA filtered laminar flow air is supplied above the station's work surface; much of the air is captured and is HEPA filtered before release into the room (right).
Reproduced courtesy of Allentown Caging Co., Inc.

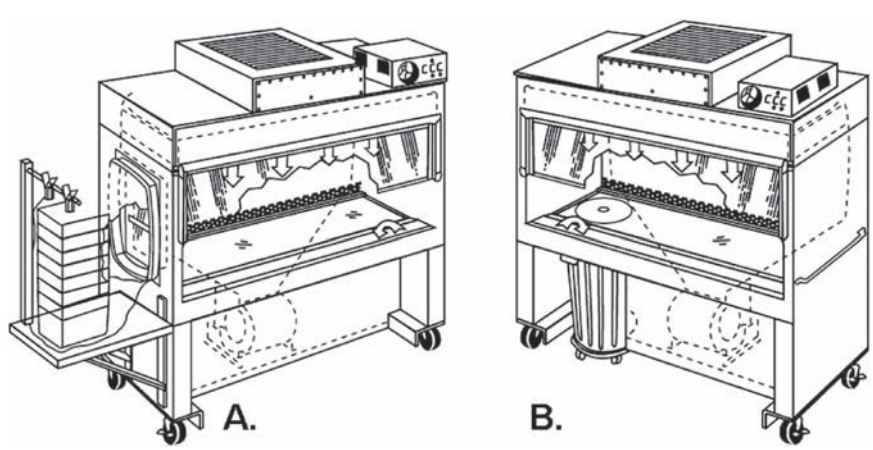


Fig. 20-2 Schematic drawings of Class II biological safety cabinets: (a) cabinet is equipped with a pass-through door in the left wall permitting placement of caging directly into a biohazard bag without removal from the cabinet (BSC); (b) cabinet contains a solid waste disposal system integrated into the work surface of the cabinet (BSC).
Reproduced courtesy of Nuaire, Inc.

Establishing the barrier at a level above the cage requires the inclusion of specific facility features. These may include the use of air or wet showers and/or air locks for personnel and equipment entry; shoe cleaners to remove particulate from the sole and other shoe surfaces; multiple corridor systems to separate dirty and clean equipment, as well as personnel activities; and special construction features (Figures 20-3, 20-4). The HVAC system is designed to provide air-pressure differential control to ensure directional airflow, and may include high-level filtration (e.g., HEPA filtration). This can be used for biohazard containment as well as for maintaining axenic, gnotobiotic, adventitious agent-contaminated and/or immunocompromised mouse lines or stocks. Most production facilities maintain and breed foundation stocks and immunocompromised lines within isolators. Use of protective personnel equipment (PPE), such as hair bonnets, laboratory coats, facemasks, shoe covers and/or gloves, is commonplace. Designated areas are frequently provided to dispense and don these items.

Fig. 20-3 Air showers (two) as observed from the barrier side of a vivarium.

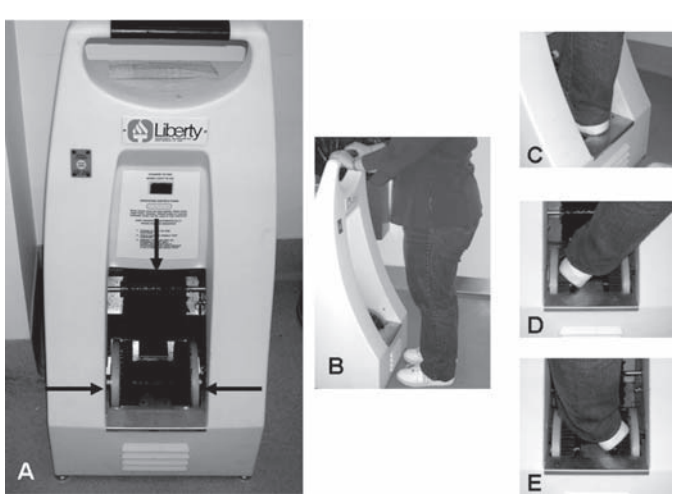


Fig. 20-4 Automated shoe cleaner utilized to remove particulates from footwear. Front (a) and side (b) views and demonstration of proper use (c, d, e). Arrows in (a) identify the rotating side and top brushes; bottom brush is not visible. Exhaust from unit is HEPA filtered. An alternative model permits effluent/particulate capture into a vacuum waste system.

II. HOUSING AND USE

Removal of rodents and their subsequent return to the vivarium increases the risk of contamination of the facility with adventitious infectious agents. It has become common to include procedure laboratories within a vivarium to reduce or eliminate the need to remove animals from the facility in which they are housed. Minor procedures may be performed within the holding room, generally within a ventilated cabinet or a BSC. Complex procedures such as surgery should be conducted outside the room in which the animals are housed. Provision of procedure laboratories within the vivarium reduces or eliminates the need to remove animals from the facility. Removal of rodents and their subsequent return to the vivarium increases the risk of their contamination with infectious agents. Depending on the operational philosophy of the institution and the nature and scope of its research program, facilities may contain as many as one procedure laboratory for every animal holding room or, more commonly, a laboratory for every four to eight holding rooms. The total number of procedure rooms will be dictated by the scope and activity of the institution's research program. Ideally, the laboratory should be situated in close proximity to the room(s) that it serves.

Rodent holding rooms and procedure laboratories can be accessed directly from the corridor or organized in suites of multiple rooms clustered around an anteroom/access corridor off the principal service corridor. Generally, a suite consists of several holding rooms and one or more procedure laboratories serving the holding rooms within the suite.

A. Holding Rooms

Animal holding rooms are often the most numerous type of room, and may comprise 50 percent or more of a facility. Dedication of the animal facility or large parts of it to maintenance of large numbers of rodents may have a significant impact on design and operations. This situation facilitates standardization of rodent holding rooms to efficiently accommodate specialized caging systems. The caging units may be static, without forced ventilation, or they may have independent ventilation systems and/or be incorporated into the building's HVAC systems for supply and exhaust air. Dedication of the facility or segments of it exclusively to rodents will enhance environmental quality for these animals.

The layout for animal rooms may be determined in part by the requirements and expectations of the research and animal-care staff. Rodent holding rooms are generally designed to maximize

the number of cages maintained while providing sufficient space for cage access and changing procedures. The size of the holding room dictates the number of cages maintained. Large rooms are more efficient; however, they may be problematic to manage, as they require the presence of husbandry personnel to change cages for extended periods, interfering with research personnel access. There is no ideal room size, but many research facilities prefer rooms with a capacity of 500–800 mouse cages or 250–400 rat cages. At this size, when utilizing high-density ventilated caging systems, a rule of thumb is that each mouse shoebox cage (11″ × 7″ × 5″) will require ~0.5 sq. ft and each rat cage (19″ × 10″ × 7″) ~1 sq. ft of floor space. Therefore, holding rooms will be approximately 250–400 sq. ft. There is no ideal room size that is best for all circumstances. Greater space per cage will be required if ergonomic considerations limit the minimum and maximum height of the lowest and highest shelves on the rack. Most racks for housing rodent cages occupy a rectangular footprint, and maintain cages on multiple tiers. Racks are either double-sided, with cages accessed from both sides, or single-sided, requiring access from one side. Two commonly utilized room configurations for this type of rack installation are illustrated in Figure 20-5. There has been no standardization in the size of cages and racks from different manufacturers; however, many double-sided racks fit a footprint of 6 feet long by 2.5 feet wide, and single-sided racks are approximately 1.5 feet wide. These dimensions and work/circulation spaces around the cage racks in large part determine the length and width of the animal rooms. The library-style configuration, fitted with double-sided or both double- and single-sided cage racks, is more efficient, as it provides a greater cage housing density; however, it limits personnel access during cage-changing and is less productive, as racks must be relocated for cage-changing. The racks, when loaded, may weigh upwards of 1,000 pounds, and be cumbersome to move distances. Mobile racks are located perpendicular with respect to the long axis of the room, positioned to provide ~2.5–4 feet of space between them. If there is sufficient room width, racks can be located on both sides of a central corridor within the room. The internal room corridor-style contains either single-sided racks positioned along the long axis of the room providing a single corridor (narrow room) or a combination of single- and double-sided racks creating two or more internal room corridors (wider rooms). This style is less efficient with respect to cage capacity

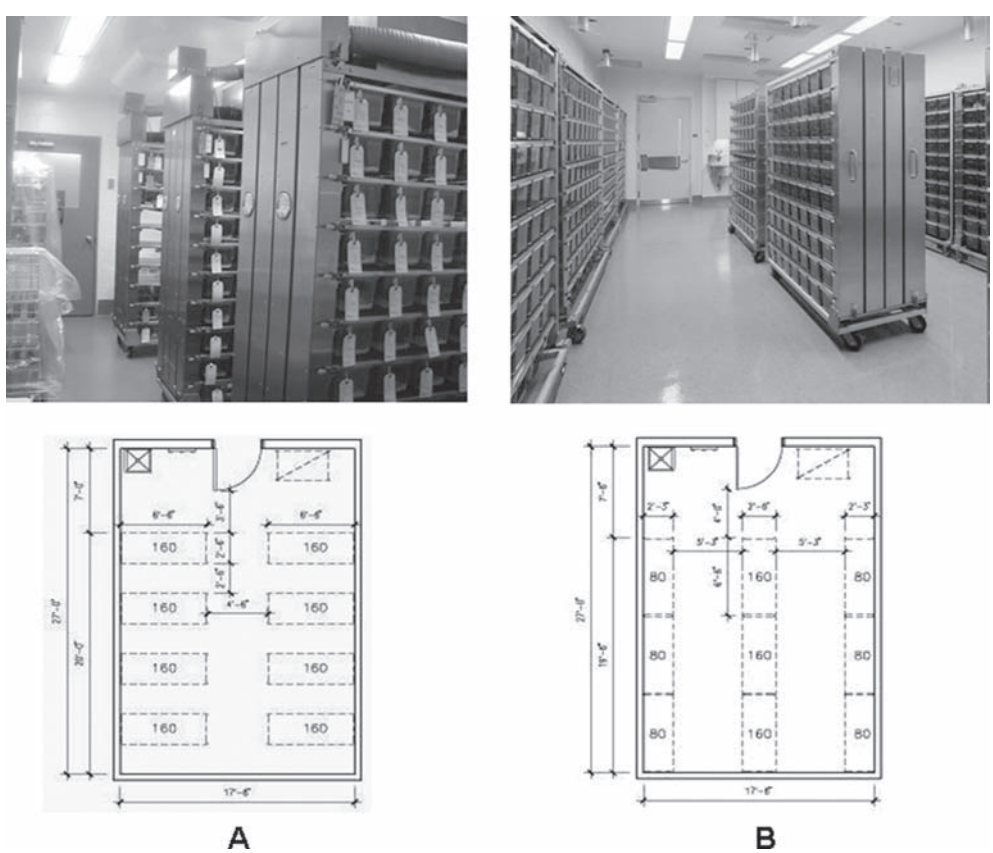


Fig. 20-5 Two commonly utilized room configurations for rack installation. (a) The *library style* configuration is more efficient; however, it limits personnel access during cage-changing and is less productive as racks must be relocated for cage-changing. (b) The *internal room corridor* style is less efficient with respect to capacity but is easier to service, as the equipment and materials used for cage-changing are located and moved within the internal corridors.

but is more efficient to service, as the equipment and materials used for cage-changing are situated and moved within the room's internal corridors. The internal room corridors are generally 4′– 6′ wide at a minimum – wide enough to permit a ventilated cabinet or BSC to be moved down the corridor perpendicular to the racks. With this layout, cages can be changed without relocating racks and investigative staff's access to their animals is easier during periods in which cages are being changed and serviced. Equipment costs are higher with this arrangement, as it requires a greater number of single-sided racks, which generally carry a premium. Regardless of layout, space needs to be allocated for a ventilated cage station(s) and maintenance of ancillary supplies and equipment. The minimum number of ventilated cage-change stations is one per room. It is not generally advisable to move the stations from room to room. Depending on the intensity of investigators' need to access their animals and the number of investigators using a room, multiple stations may be required. A general rule in biomedical research facilities is to have a maximum of 300–400 mouse cages per ventilated cage-change station or BSC. One manufacturer has recently introduced a rack which holds cages in a carousel arrangement (Figure 20-6).

Fig. 20-6 A carousel-style rodent cage rack.
Reproduced courtesy of Animal Care Systems, Inc.

The rack's footprint is square rather than rectangular. Cages are accessed by rotating the carousel on which the cages are maintained. Considerably higher cage-stocking densities are theoretically achievable with this system.

Rodent holding rooms are generally equipped with a hand-washing or larger sink in close proximity to the door through which personnel gain access. Alternatively, a sink can be provided in the anteroom, if animal holding rooms are configured in a suite, or in the corridor, allowing the sink to serve multiple rooms. Disinfectant gel or alcohol foam dispensers can also be installed near the access door for hand sanitization. Rodent holding rooms are provided with a monolithic floor (with integral 4″–8″ base cove), ceiling and walls. View panels in room doors should be equipped with shutters or light-restricting glazing, and doors should have a closer and a drop seal or sweep. A wall-mounted implement rack should be provided for holding a broom, mop, and other room-dedicated cleaning implements. In-room water distribution piping will be needed if automatic watering is planned, and wall- and/or ceiling-mounted electrical outlets should be provided to support ventilated caging systems, ancillary equipment and research needs. Door view panels, if used without shutters, should be coated with an appropriate material to filter out light visible to rodents. Rodents do not see red light, so filtering out all visible light up at least to the start of the red range (i.e. 620 nm) will provide red light visible to humans but reportedly not to rodents (Sun *et al*., 1997; Lyubarsky *et al*., 1999). The author has recently determined that the red film-coating specified by several architectural design firms who specialize in vivarium design does not meet the desired performance standard. Transmission of 400- to 500-nm wavelength light, which is in the mouse and rat's visible spectrum, was detected. The author has used a laminated glass with an integrated red-chocolate film manufactured by Solar Graphics Inc., Clearwater, FL.

Timer-controlled (local rotary or digital, or centrally by the building management system(BMS)) bi- or tri-level lighting is recommended. Low-level lighting, activated during the light phase of the diurnal cycle, is controlled by a 24-hour timer. Supplemental lighting is provided for personnel when they enter the room during the light phase. Supplemental lighting can be activated by an occupancy sensor (motion sensor or infrared detector), push-button or rotary timer, all of which provide a time-out function to ensure that lighting returns to the low level when personnel have vacated the room. Supplemental lighting can also be used to provide low-level lighting during the dark phase of the cycle if personnel access is necessary. However, rodents are very sensitive to disruptions of light cycles, and short-duration light exposure may interfere with research results. Because of concerns for light-induced retinal damage in albino rodents, some advocate having a single light-level of approximately 30 foot-candles measured 3 feet from the floor, which is bright enough to perform routine animal-care activities within the room. Alternatively, for working in the room after "lights out," incandescent darkroom

(red), sodium or infrared lamps can be provided for dark-phase evaluation of animals (McLennan and Taylor-Jeffs, 2004). Outlets serving ventilated caging systems and essential equipment should ideally be provided with emergency power. Other services to consider include data jacks, a phone outlet, and hardware to support wireless communication.

In many vivaria, holding rooms must be designed with the flexibility of housing a variety of species. Special features are included when the room must be capable of holding large animals in addition to rodents. Floor drains are generally not needed or desirable in rooms dedicated solely to rodent housing, as they can serve as an odor source or harbor vermin. When provided, drain assemblies should be sealable, with a tight-fitting, solid cover that fits over or replaces the perforated drain cover when not in use. In rooms equipped with trenches or floor sinks for use with large animals, it is desirable to have solid trench/floor sink covers to preclude debris from falling into the recess, or loose rodents from entering. Alternatively, they could be left open to facilitate cleaning and a bumper guard installed on the wall above the trench drain to prevent rack wheels from falling into the trench. Lighting control systems may need to be different from those used in rooms dedicated solely to rodents; as large animals are more likely to activate occupancy sensors. Furthermore, a dual- or tri-level lighting system may not be desirable or necessary for non-rodent species.

B. Procedure Laboratories

For disease control reasons many institutions discourage removing animals from and returning them to the holding room, preferring, whenever possible for routine procedures, to conduct procedures in a ventilated changing station or BSC within the holding room. Complex research procedures may need to be conducted in laboratories within the vivarium. Procedure laboratories can vary in size, from as small as 60 sq. ft to more than 200 sq. ft. The size is based on the proposed activities and the necessary equipment to support laboratory functions. Generally, it is preferable to restrict laboratory use to a single investigative group at a time to avoid cross-contamination between investigative and/or animal groups. The author recommends including an equal number of small (~80 sq. ft) and medium-sized (~150 sq. ft) laboratories in rodent facilities serving multidisciplinary research programs. If program needs dictate, considerably larger procedure laboratories may be required. Facilities generating genetically engineered mice may locate the laboratory used for embryo manipulation and related activities within the vivarium to avoid the potential for cross-contamination, as animals are frequently transferred between the laboratory and housing rooms. These laboratories can be quite large (several thousand square feet), and may be subdivided into areas supporting different activities such as surgery, microinjection and cryopreservation. Multi-modality imaging laboratories are also becoming more common within vivaria to support rodent animal model development and use programs (Figure 20-7). Imaging technologies include isotopic methods such as positron emission tomography (microPET), single photon emission computer tomography (SPECT) and gamma camera imaging. Non-isotopic methods may also be provided, such as optical techniques (bioluminescence and fluorescence), computerized tomography (microCT), magnetic resonance imaging and spectroscopy (MRI and MRS), and high-frequency ultrasound (Budinger *et al*., 1999; Foster *et al*., 2000; Paulus *et al*., 2000; Allport and Weissleder, 2001; Wirrwar *et al*., 2001; Benveniste and Blackband, 2002; Chatziioannou, 2002; Contag and Bachmann, 2002; Ritman, 2002).

Fig. 20-7 A rodent-imaging laboratory containing various types of imaging equipment and support equipment. A combination SPECT and CT scanner is present in the right foreground, a microCT scanner in the right background is in partial view, a biological safety cabinet is located in the left foreground, and an optical imaging system can be seen in the left background.

Procedure laboratories should be equipped with casework providing both a work surface and storage; kneeholes are provided for bench-top activity. Lockable casework facilitates assignment of individual casework to research staff for supply storage. Procedure rooms should be equipped with a sink, and may also include high-intensity lighting (e.g. wall- or ceiling-mounted examination or surgical lights; laboratory and/or medical gases and services such as vacuum, carbon dioxide, oxygen and/or medical-grade air; a point exhaust system for waste anesthetic gas scavenging; a refrigerator; a BSC, ventilated cabinet and/or chemical hood; and sufficient electrical and data outlets to support equipment. Figure 20-8 contains a photograph of a typical rodent procedure laboratory. Laboratories used for prolonged housing should have environmental systems and timed light control, as described for holding rooms.

Procedure laboratories are generally suitable for, and meet regulatory requirements for, conducting surgical procedures on rodents. Depending on user preference and/or the specific surgical procedure conducted, surgery may be conducted at a

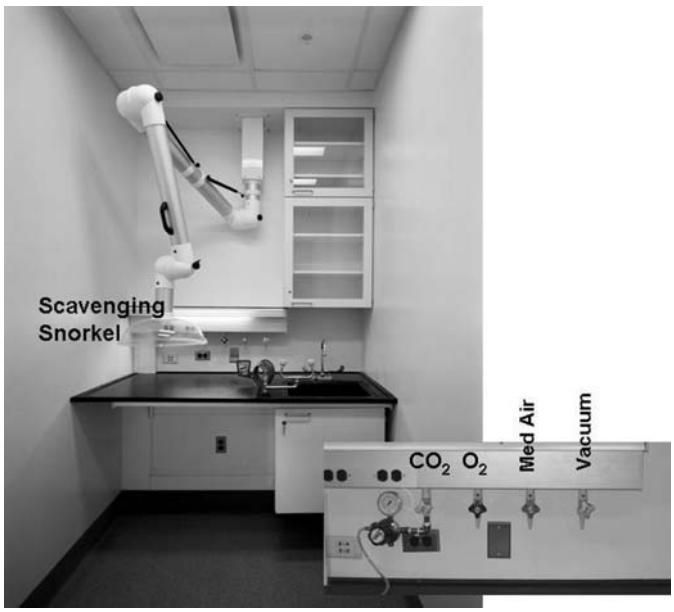


Fig. 20-8 A typical rodent procedure laboratory containing a scavenging snorkel arm, sink, various gases for anesthesia (O_2 and medical air) and euthanasia (CO_2), and vacuum. A kneehole in the casework is for seated bench work.

bench provided with a kneehole or a retractable work surface or, alternatively, on surgical tables. Facilities and management practices for conducting rodent surgery have been described elsewhere (Cunliffe-Beamer, 1993; Brown, 1994).

C. Caging Systems

Considerable changes have occurred in the manner in which rodents are housed since they were first introduced into the laboratory. Early cages were made of wood. Glass and stainless-steel cages were introduced subsequently, markedly improving sanitation and durability. As glass was heavy and subject to breakage, and stainless-steel cages were opaque, heavy and expensive, the development of techniques to mold plastic, as well as the development of its transparency and its ability to withstand washing at 180°F, led to the introduction and subsequently the widespread use of molded plastic cages (Hessler, 1999). A variety of plastic polymers, including polystyrene, polycarbonate (Lexan® or Macrolon®), polypthalate carbonate (high-temperature polycarbonate), polyetherimide (Ultem®), polysulfone (Udel®) and polyphenyl-sulfone (Radel R®), have been utilized. Each polymer differs with respect to resistance to deterioration from chemical and heat exposure, impact strength, and cost. Concerns have been raised that bisphenol A (BPA), the principal constituent of polycarbonate, polypthalate carbonate and polysulfone, may be released from thermoplastic caging and bottles either as an unpolymerized constituent or as a result of degradation (Koehler *et al*., 2003). Degradation is most likely to occur as a result of hydrolysis at high temperatures; however, Howdeshell *et al*. (2003) have observed that, as polycarbonate cages age, there is a marked increase of BPA leaching at room temperatures. BPA, an "estrogen mimic," has been associated with meiotic disturbance in laboratory mice whose polypthalate carbonate cages and bottles were inadvertently exposed to alkaline detergent during cage-washing, and may also be released as the thermoplastic degrades with use (Hunt *et al*., 2003).

1. *Static Micro-Isolator Cages*

The evolution of caging systems and associated equipment for mouse husbandry escalated rapidly during the late twentieth century. Cages with filters, early on, demonstrated the effectiveness of isolator caging for the control of infectious diseases (Kraft, 1958; Kraft *et al*., 1964; Serrano, 1971). The introduction of a new filter top design and mass air displacement unit for cage-changing in the early 1980s set off a revolution in rodent husbandry (Sedlacek *et al*., 1981). The Sedlacek-designed static micro-isolator (MI) cage was marketed commercially and was implemented broadly within the US. While poor micro-environmental (MiE) air quality was a concern with earlier filter lid designs, air quality was of greater concern in the Sedlacek MI cage (Corning and Lipman, 1991; Hasenau *et al*., 1993). A second commercial static MI cage was soon made available, the principal differences being the amount of surface area exposed on the filter top and the grade of filter media employed; however, no substantial differences in MiE air quality resulted (Corning and Lipman, 1991), the reason being that air exchange in static MI cages occurs primarily at the cage–lid interface, not at the filter, and air exchange rates in static MI cages were markedly reduced as compared with open cages (Keller *et al*., 1989).

Static MI cages, despite their disadvantages, still play an important role in animal research. They retain allergenic proteins within the cage, reducing their levels in the macroenvironment (MaE) (Sakaguchi *et al*., 1990). Since allergy is among the most important occupational diseases affecting animal handlers, this advantage is significant (ILAR, 1997). They are useful for studies in which containment at the cage level is desirable (Bhatt and Jacoby, 1983). Static MIs are the author's preference when housing rodents exposed to infectious agents or hazardous chemicals. Recently, a completely disposable MI system, consisting of a shoebox cage, isolator lid, feeder and water bottle, manufactured of polyethylene terephthalate has become available. This system is of benefit for housing animals exposed to highly hazardous agents. Static MIs can be placed in a secondary enclosure, such as a negative flow mass air displacement unit (MADU), a BSC or a chemical fume hood, for an additional level of containment. When used for hazardous agent containment, static MIs should preferably be opened and the contaminated animals and cage contents handled within a BSC or fume hood, depending on the hazard employed. Intracage ventilation and, as a result, MiE conditions improve when

static MIs are housed within a MADU, because of increased airflow over the filter top (Corning and Lipman, 1992).

There are four methods of addressing poor MiE air quality in static MIs (Memarzadeh, 1998):

1. Change cages at sufficient frequencies (Corning and Lipman, 1991)
2. Utilize a contact bedding with desirable performance characteristics (Perkins and Lipman, 1995; Smith *et al*., 2004)
3. Reduce MaE relative humidity (RH) levels (Corning and Lipman, 1991)
4. Increase MaE temperature without altering the moisture content in the air.

Static MIs may influence the biology of the mice housed within, as the growth rate of mice housed in static MIs was found to be significantly greater than for those housed in cages without a lid (Baer *et al*., 1997).

The following conclusions determined from a comprehensive study evaluating the performance of static MIs using computational fluid dynamics (CFD) should be considered when designing rodent holding rooms utilizing static MIs (Memarzadeh, 1998).

1. Ceiling or high-level room exhaust resulted in lower room temperatures than low-level exhausts, primarily because of convective heat flow generated from the cages
2. Low-level exhaust improved micro-environmental ventilation slightly as compared to high-level exhaust when racks containing the cages were housed parallel to the walls
3. Increasing room exchange rates above 5 air changes per hour (ACH) did not significantly improve intra-cage ventilation
4. The type of supply diffuser or exhaust register utilized did not significantly alter macro- or micro-environmental conditions.

2. *Ventilated Caging Systems*

In the late 1980s and early 1990s, concern regarding poor MiE air quality in static MIs, while at the same time the demand for mouse housing was burgeoning, served as the major stimulus for the development of and transition to individually ventilated caging systems (IVCs) from static MIs. Although the concept of directly ventilating mouse caging was first conceived at the Jackson Laboratory (*Jax*) in the mid-1960s, the first major installment of IVCs, which occurred at *Jax*, did not take place until 1978, as further design refinements were necessary (Les, 1983; Hessler, 1999). The first commercial system became available in 1979 (W. Thomas, personal communication, 2004). Subsequently, numerous IVCs have subsequently been developed and sold. Although the available IVCs have the common goal of improving intra-cage ventilation and, therefore, MiE conditions, manufacturers have approached this goal using a variety of design concepts. Available caging systems and their operational designs have been reviewed (Lipman, 1999). Another important advantage of IVCs is the ability to increase rodent cage housing density significantly with some IVC systems as compared to cages without filter tops or static MIs. Rodent housing and facility design have been so greatly impacted by the advent of ventilated caging that a detailed discussion of this subject is included here.

a. Types of IVCs

There are two principal classes of IVCs based on their operating design: intra-cage supply/perimeter capture, and intra-cage supply/intra-cage exhaust systems (Lipman, 1999). The latter group can be further divided into direct, indirect and combination subtypes, depending on whether the supply or exhaust air passes through a filter, at the level of the cage, before entering or exiting the cage. Figure 20-9 provides schematic representations of the various systems.

Intra-Cage Supply/Perimeter Capture HEPA filtered air is supplied directly, at the level of the cage, resulting in its pressurization. Cage effluent escapes primarily at the filter top/shoebox cage interface, and is captured at the interface and also at the filter by a three-sided U-shaped channel or a canopy. These systems can only operate with positive intra-cage pressure. Select independent experimental evaluations have been published on this system type (Choi *et al*., 1994; Huerkamp and Lehner, 1994; Huerkamp *et al*., 1994; Perkins and Lipman, 1996; Tu *et al*., 1997).

Intra-Cage Supply/Intra-Cage Exhaust

1. *Intra-cage supply/intra-cage exhaust (direct)*. Air is supplied directly to the cage lid or bottom, and exhausted directly from the lid or from a plenum beneath the cage. Many of these systems can be operated with either positive or negative intra-cage pressure by electronically or mechanically altering the quantity of supply and exhaust air by adjusting blower speed or dampers. Independent evaluations of this system type have been published (Hoglund and Renstrom, 2001; Renstrom *et al*., 2001; Baumans *et al*., 2002; Memarzadeh *et al*., 2004).
2. *Intra-cage supply/intra-cage exhaust (indirect)*. Supply air is provided and exhaust removed through a filter in the cage lid, which resides directly below a positive and negative plenum or duct. Supply air diffuses from the plenum or duct through the filter into the cage, while the reverse occurs for exhaust. Systems can be operated with either positive or negative intra-cage pressure by altering the position of dampers manually, or electronically altering

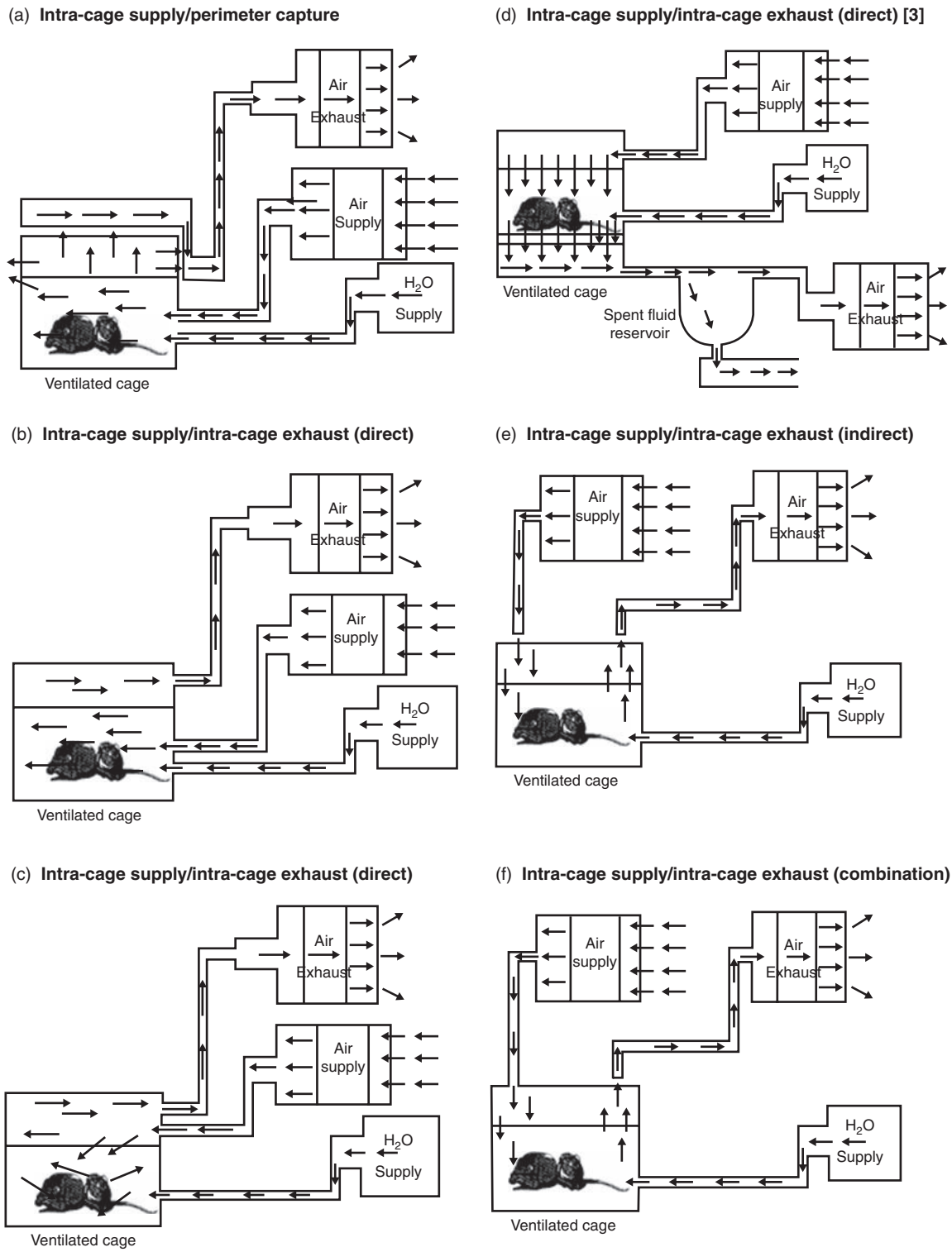


Fig. 20-9 Schematic representations of types of commercially available ventilated caging systems. Notice that all systems are shown with automatic watering. Vectors representing airflow are shown for illustrative purposes only, and do not necessarily reflect airflow patterns within the cage.

Reproduced from Lipman (1999).

the quantity of supply and exhaust air by adjusting blower speed and/or the pressure drop across control valves situated in the supply and exhaust ducts. Independent evaluations of this system type have been published (Huerkamp and Lehner, 1994; Clough *et al*., 1995; Perkins and Lipman, 1996; Tu *et al*., 1997; Reeb *et al*., 1998; Hoglund and Renstrom, 2001; Reeb-Whitaker *et al*., 2001; Renstrom *et al*., 2001; Langham *et al*., 2006).

3. *Intra-cage supply/intra-cage exhaust (combination)*. One IVC manufacturer offers an optional valve(s) on its isolator top that is actuated when the cage is placed on the rack and closed when the cage is removed. The valve, which is placed on the supply, provides direct inflow of air, circumventing the filter in the lid and maintaining intra-cage positive pressure.

b. Advantages

IVCs offer numerous advantages over static systems in addition to dramatically improving MiE air quality (Keller *et al*., 1983; Wu *et al*., 1985; Iwarsson and Noren, 1992; Lipman, 1992; Choi *et al*., 1994; Huerkamp and Lehner, 1994; Yoshida and Tajima, 1995; Perkins and Lipman, 1996). The concentrations of intra-cage NH_3 and CO_2 are considerably lower in IVCs when compared with static MIs maintained under the same MaE conditions. Further, the day on which NH_3 is first detected is delayed in IVCs. Not only is the intra-cage air quality improved; the variability in MiE air quality observed among static MIs housed in the same MaE is also reduced or eliminated in IVCs (Perkins and Lipman, 1996). As less NH_3 is generated in ventilated cages, MaE air quality is improved for personnel working in animal holding rooms and cage-wash. In most facilities, IVC changing is delayed to weekly or even longer, depending on the strains of rodents housed, their experimental use and housing density, and the institutional perspective (Reeb *et al*., 1998). In contrast to static MIs, which frequently require twice-weekly changing, a weekly or longer cage-change interval translates to considerable labor savings. In addition to the time saved, the quantity of bedding used is also reduced and the longevity of cage components, especially those made of thermoplastic and autoclaved, is also increased, resulting in substantial operational savings.

Another significant advantage is the opportunity markedly to increase stocking density when IVCs are employed. In contrast to static MIs housed on a shelf rack, IVCs can house up to 100 percent more animals, depending on the systems compared, while occupying the same footprint. IVCs can significantly increase housing capacity, permitting institutions to substantially decrease space dedicated to mouse housing, or house considerably more animals in the space available. As the MiE air volume is considerably smaller than that of the MaE, the MiE can be ventilated at higher rates using less supply air than is needed to ventilate the MaE. This feature, along with the capability of exhausting IVC rack effluent (which contains a considerable component of the thermal load generated by the animals) directly into the building's HVAC system, allows for the potential of using lower air exchange rates to ventilate rodent holding rooms (Lipman, 1993; Clough *et al*., 1995).

IVCs can also provide, depending on the specific system used, an additional protective barrier to animals housed within the cage (Cunliffe-Beamer and Les, 1983; Lipman *et al*., 1993; Myers *et al*., 2003; Bohr *et al*., 2006). Systems pressurizing the cage with HEPA filtered supply air provide cage occupants with an additional level of protection from contamination. The effectiveness of IVCs, in this capacity, has been demonstrated experimentally (Lipman *et al*., 1993; Bohr *et al*., 2006).

As the effluent from IVCs may be HEPA filtered before release into the room, or, alternatively, directed into the building's HVAC exhaust system, the concentration of allergenic particulates to which personnel are exposed in the MaE may be reduced with particular IVC designs. Particulates, detected using settle plates, were reduced by 99 percent and 94 percent in comparison with open cages when one IVC was operated in either positive or negative modes, respectively (Clough *et al*., 1995). In another study, murine urinary allergens were orders of magnitude lower in two types of IVCs, operated at both positive and negative intra-cage pressure, when compared with open cages (Renstrom *et al*., 2001). Langham *et al*. (2006) recently compared a single IVC system operated at both positive and negative intra-cage pressure with HEPA-filtered rack effluent released into the room or into the building's exhaust system, and static MI cages. They found that large particles were reduced in rooms with the IVCs operated in the various pressure and exhaust combinations; however, the number of small particles did not differ in rooms with any of the ventilated caging combinations or static MIs. The reduction of MaE particulate may not be offered by all IVCs, as several systems operate by pressurizing the cage, attempting to capture cage effluent after it escapes from the cage. Leakage of cage effluent into the MaE has been detected with these systems using a tracer gas (Tu *et al*., 1997).

c. Operational and Selection Criteria

Although the advantages of IVCs are clear, there are important considerations when selecting or using these systems. Users must clearly understand the operating principles of the system they use. Specific systems differ with respect to the method of introduction and quantity of air supplied to each cage. The ideal intra-cage ventilation rate for IVCs is unknown and is likely dependent on numerous factors, including species, strain- or stock-housed, cage population, bedding, and the specific IVC used. An ideal rate in one situation may be insufficient or excessive in another. The criteria used to select intra-cage ventilation rates should be based on performance standards. Reeb-Whitaker *et al*. (2001) evaluated ventilation rates and cage-change frequency with respect to breeding performance, weanling weight and growth, plasma corticosterone

levels and pathology in C57BL/6J mice, and determined that ventilating cages at 60 ACH and changing every 14 days was ideal. Another study conducted by the same group concluded that intra-cage ventilation rates should be increased from 60 to 100 ACH when housing breeding trios and pups in lieu of adult males if the same changing frequency and intra-cage NH_3 concentrations are to be maintained (Reeb *et al*., 1998). Unless determined otherwise, the author recommends that ventilation rates be established in IVCs so that, prior to cage-change, MiE NH_3 and CO_2 are <25 and 5000 ppm, respectively, and temperature and RH fall within the limits prescribed in the *Guide* (ILAR, 1996). Further, intra-cage air speed, at locations that cage occupants would expect to encounter, should be ≤ 50 linear feet per minute (lfpm), a rate considered to be still air in human environments, and unlikely to cause appreciable physiologic effect in most species (Clough, 1987; ASHRAE, 2001). It is extremely difficult to obtain accurate information on ventilation rates for IVCs. The technology available to measure ventilation rates is designed for evaluating rooms or buildings; it is not designed to accurately evaluate enclosures the size of rodent cages, which have a volume <1 cubic foot, or whose air supply or exhaust rates may be <0.5 cubic feet per minute (cfm). Several groups have used tracer gas (SF_6) decay to evaluate air exchange rates in ventilated cages (Clough *et al*., 1995; Tu *et al*., 1997; Reeb *et al*., 1998). Although more accurate than other techniques, the small cage volume limits accuracy (Tu *et al*., 1997).

Excessive intra-cage ventilation, especially when air is supplied at the level of the cage, may lead to chilling and dehydration, especially in neonates and hairless mutants. The speed of air to which animals are exposed affects the rate at which heat and moisture are removed from an animal. Air at 20°C moving at 60 lfpm has a cooling effect of approximately 7°C (Weihe, 1971). It may be necessary to increase MiE temperature when housing animals in IVCs with high intra-cage air velocities, when housing neonates, hairless mutants or single animals, or when contact bedding is unavailable or is a type that does not provide the animal with the ability to nest. Pheromone dilution may also be problematic when breeding particular *Mus* species, stocks or strains (Lipman, 1999). Huerkamp *et al.* (1994) have demonstrated a negative synergistic effect between ventilated cages and the use of automatic watering systems leading to increased mouse pup mortality. Further, they demonstrated that pups reared in IVCs were smaller than those reared in static MIs and attributed the change to intra-cage ventilation. Using preference testing with BALB/c mice, Baumans *et al.* (2002) concluded that the mice avoid cages with high intra-cage ventilation rates (up to 100 ACH), but the use of nesting material counteracted this avoidance.

There are considerable differences in IVC ventilation rates, based on the manufacturer, the system type, and even the age of the system. A comparison of three commercial systems revealed that intra-cage ventilation differed by as much as 88 percent (Tu *et al*., 1997). It is also notable that velocities exceeding 50 lfpm were detected in two of the three IVCs evaluated, with speeds approaching 100 lfpm detected in one system (Tu *et al*., 1997). Ventilation rates can be adjusted in most IVCs by adjusting exhaust and/or supply fan speeds or dampers.

Additional considerations when utilizing and selecting IVCs include heat load, noise generation, power requirements and failure, vibration, and sanitization. As IVCs enable users to increase stocking density by up to 100 percent, the heat load generated by the animals may be of considerable magnitude. The heat load generated by the supply and exhaust blowers when combined with the animals' thermal load, especially in holding rooms with marginal temperature control, may exceed the HVAC system's cooling capacity. Frequently, this issue can be resolved by directly venting the IVC exhaust into the building's HVAC system, since much of the thermal load is contained within the exhaust effluent.

IVC blowers generally utilize 110-V alternating current; some manufacturers are providing transformers and using low-voltage blowers to reduce noise generation. Depending on the system's design, the exhaust and supply blowers may be interconnected, requiring a single outlet, or each blower (supply and exhaust, if equipped) may require its own. It is prudent to place IVCs on circuits served by emergency generators, because the design of many IVCs does not provide the capability for passive ventilation in cases of power failure. In fact, some systems employ solid tops, without filters, and attach firmly to the cage below with a gasket and/or clips. It may be critical in certain installations to ensure that exhaust and supply blower operation are interconnected functionally, such that if one fails the other is automatically disabled. For example, if it is critical that the IVC provides product protection, then supply-blower failure must be accompanied by exhaust shutdown. If this feature is not implemented, cages will develop negative pressure if the supply blower fails or its output is diminished. Most systems are available with warning lights, magnehelic gauges and audible and/or voltage alarms that require either active or passive monitoring by facility staff.

Noise generated by exhaust and/or supply blowers is a consideration that depends on system type and the number of IVCs maintained per holding room. Noise must be addressed from two perspectives; the effect(s) of MaE noise on personnel servicing and working within the holding room, and the effect(s) of MiE noise on the cage occupants. The impact of noise on both animal behavior and physiology has been described (Peterson, 1980; Clough, 1982). Rodents' hearing range overlaps, only partially, with that of man; their range extends to ultrasonic frequencies not heard by humans (Sales and Pye, 1974). Limited data have been reported on noise generated by IVCs (Clough *et al*., 1995; Perkins and Lipman, 1996). Both MiE and MaE noise at frequencies between 31.5 and 16,000 Hz were evaluated in three commercial IVCs (Perkins and Lipman, 1996). All three systems produced room noise that was significantly higher than room background. One

unit generated more noise (80 dB) than the other two units (74 dB) evaluated. Recognizing that the dB scale is logarithmic, this difference is discernible. MiE noise was found to be higher at lower frequencies, compared with both MaE noise and noise generated at higher frequencies, in the three systems evaluated. The significance of these findings for rodents was unclear. It has been speculated that rodents have a higher tolerance for low-frequency than for high-frequency noises (Pekrul, 1991). However, the authors did not evaluate ultrasonic frequencies. Ultrasonic frequencies were not detected in another evaluation of a single IVC (Clough *et al*., 1995). A logarithmic equation is used to determine the increase in dB levels when additional units generating equal amounts of noise are placed in a room. There is an increase in 3 dB with the second, 1.8 dB with the third, 1.2 dB with the fourth, and <1 dB for each successive unit added (American Conference of Governmental Industrial Hygienists, 2004). Therefore, in a room containing four units generating 80 dB each, the room noise level would be 86 dB – a level above the ACGIH-established 8-hour TWA of 85 dB (American Conference of Governmental Industrial Hygienists, 2004).

The physiologic effects of continuous low-level vibration have not been carefully investigated, to the author's knowledge. IVCs with blowers attached directly to the rack are more likely to generate vibration at the cage level. Whereas behaviorists are concerned about environmental stimuli provide timing cues, IVC units are operated continuously, and therefore would be unlikely to have any effect in this regard. In any event, system manufacturers have taken some or all of the following steps to reduce or eliminate intra-cage vibration:

- placing rack-mounted blower housings on rubber and/or spring-loaded mounts (Figure 20-10);
- placing housing blowers on a rack/shelf separate from the caging (Figure 20-11);
- using flexible plastic hose connectors between the rack air distribution system and the blowers (Figure 20-11); and/or
- using the building's HVAC system to provide supply and exhaust air (Figure 20-12).

d. Sanitation

Because IVCs have extensive air distribution systems, they are considerably more difficult to sanitize than a standard shelf rack. In general, blowers, shelves and/or access panels must be removed and/or opened before placing an IVC in a rack washer. Access to all plenums and ducts on the cage rack may not be possible with every system. Extensive washing by hand is frequently required, as the air distribution system may not be sanitized adequately in a rack washer because of limited access to the washer spray. There is no consensus on the sanitization frequency for IVCs. Systems are broken down and sanitized annually at the author's institution, unless there is a change in the animals' health status or special circumstances dictate more frequent sanitization. Prefilters, if supplied on IVCs, often require changing or cleaning more frequently, depending on the specific system and the bedding used. The blower units must be disassembled for cleaning since specific components, including the fan motor and

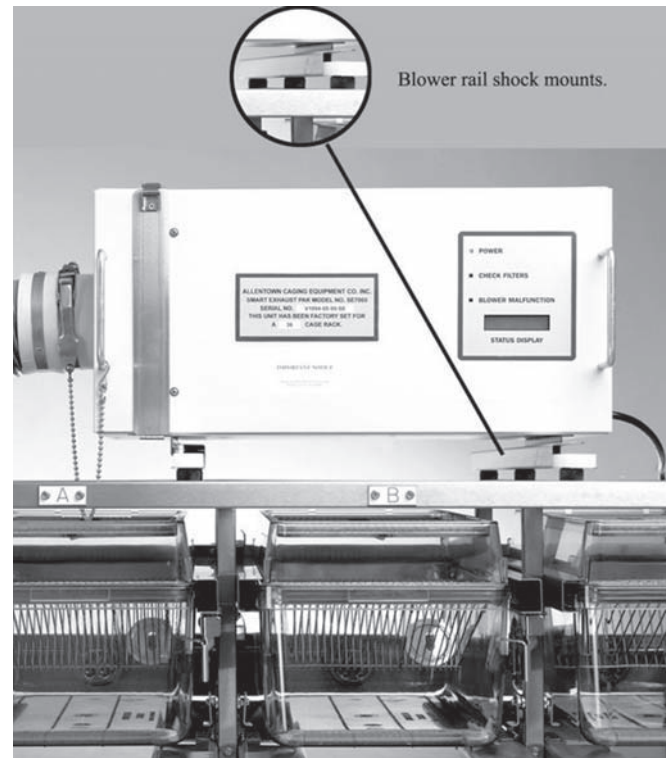


Fig. 20-10 Vibration-dampening mounts on a rack-mounted blower. Reproduced courtesy of Allentown Caging Co., Inc.

Fig. 20-11 Wall-mounted supply and exhaust blowers. The exhaust blower is directly connected to the building's exhaust system.

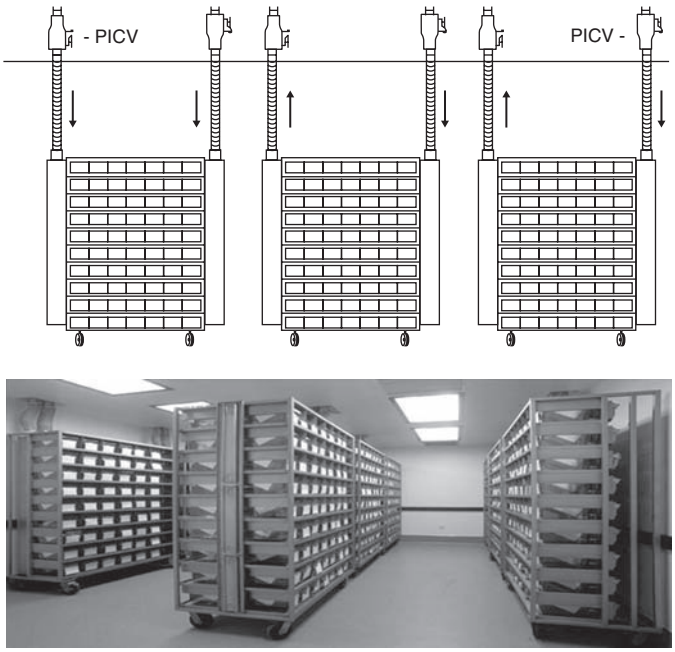


Fig. 20-12 Schematic and photograph of individually ventilated cage racks of the direct supply, direct exhaust type. PICVs (two per rack) are located in interstitial space above.
Schematic courtesy of Phoenix Corporation, Inc.

the HEPA filter, cannot be sanitized with liquid. If sanitization of these components is required, gas agents may be used. Although labor-intensive, IVCs can be decontaminated *in situ* by bagging the unit or isolating the holding room and sterilizing the room and its contents with gas sterilants such as paraformaldehyde, chlorine dioxide gas or vaporized hydrogen peroxide.

e. Use with Hazardous Agents

Because of the difficulty in sanitizing IVCs and the potential for unfiltered cage effluent to be released from some systems, considerable thought must be given to their use before housing animals that are infected with or exposed to hazardous agents. The release of unfiltered cage effluent into the MaE, which has been demonstrated with some systems, raises an additional concern when utilizing hazardous agents (Tu *et al*., 1997).

The use of IVCs to house animals on studies with hazardous agents should be limited to systems that do not release cage effluent into the MaE without first passing it through an appropriate filter and/or releasing exhaust effluent directly into the building's dedicated HVAC exhaust system. Several IVCs can be operated with negative intra-cage pressure, and therefore are preferable for these studies. A specialized IVC, with features including a positive latching solid (filterless) lid with perimeter gasket and self-closing cage fittings (which connect and seal to the rack's welded, sealed exhaust and supply plenums), interconnected redundant supply and exhaust blowers with HEPA filters, and integral battery back-up, is commercially available for use with biological hazards (Figure 20-13a, 20-13b). Systems dependent on HEPA filters for safety should be certified for filter integrity and function by certified technicians no less than annually, or more frequently as conditions dictate, as recommended for a BSC (Wilson and Chosewood, 2007). It is important to note that not all IVCs are constructed to permit easy access to test the HEPA filters.

f. Use for Euthanasia

IVCs have been designed and/or modified to use for rodent euthanasia (Feltham *et al*., 2003; McIntyre *et al*., 2007). These systems provide carbon dioxide (CO_2) gas in lieu of supply air to each cage on the rack. The system, designed by McIntyre and colleagues, requires a central CO_2 source and a thimble-equipped connection to the building's exhaust system (Figure 20-14). This system employs a program logic controller, a solenoid valve and a motorized damper. With this system, up to 140 cages of mice can be efficiently euthanized at once.

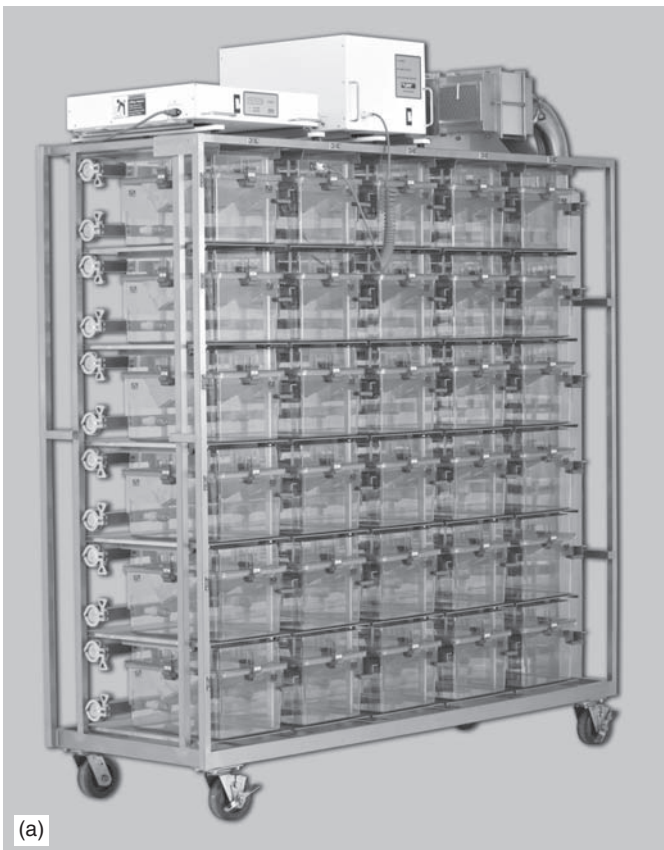
g. Integration Methods

Integration of IVC racks into animal facilities presents considerations above and beyond the method utilized to ventilate the cages. They can be integrated into facilities using a variety of methods. There are four potential methods, with several having additional permutations:

1. Room supply/room exhaust
2. Room supply/direct exhaust
3. Direct supply/direct exhaust
4. Direct supply/room exhaust.

The advantages and disadvantages of each method should be scrutinized in order to determine which best meets the current and future needs of the facility. Flexibility, operational costs and capital expenditures are several of the issues that are impacted when deciding how these systems are best integrated. Table 20-1 provides a summary of the advantages and disadvantages of each installation method.

Room Supply/Room Exhaust In this configuration, room air is drawn through the supply blower, provided by the system manufacturer, into the rack's air distribution system and is directed into each cage (Figure 20-15). Room air is typically HEPA filtered in the blower assembly. Exhaust air is extracted from the cage or collected from a plenum surrounding it by a manufacturer-supplied exhaust blower. Exhaust is generally HEPA filtered, reducing particulate and allergen release, before introduction back into the animal holding room. Unless equipped with supplemental filtration systems, such as activated carbon, this installation method does not preclude supplying and/or exhausting volatile substances (such as ammonia) back into the holding room. This method is dependent



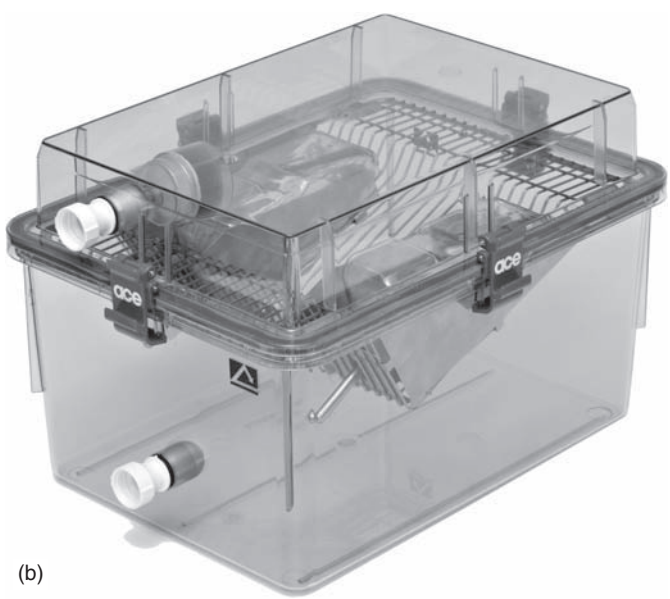


Fig. 20-13 Individually ventilated caging system (a) and cage (b) designed for biocontainment. The rack provides HEPA filtered supply and exhaust air. Seam welded stainless steel and sanitary connections are used on the supply and exhaust air distribution system. Supply and exhaust blowers provide a minimum of $-0.25''$ H_2O intra-cage pressure and are interfaced to ensure negative pressure is maintained if exhaust blower function is interrupted. Sealed cage with silicone gasket and cage exhaust prefilter. Reproduced courtesy of Allentown Caging Co., Inc.

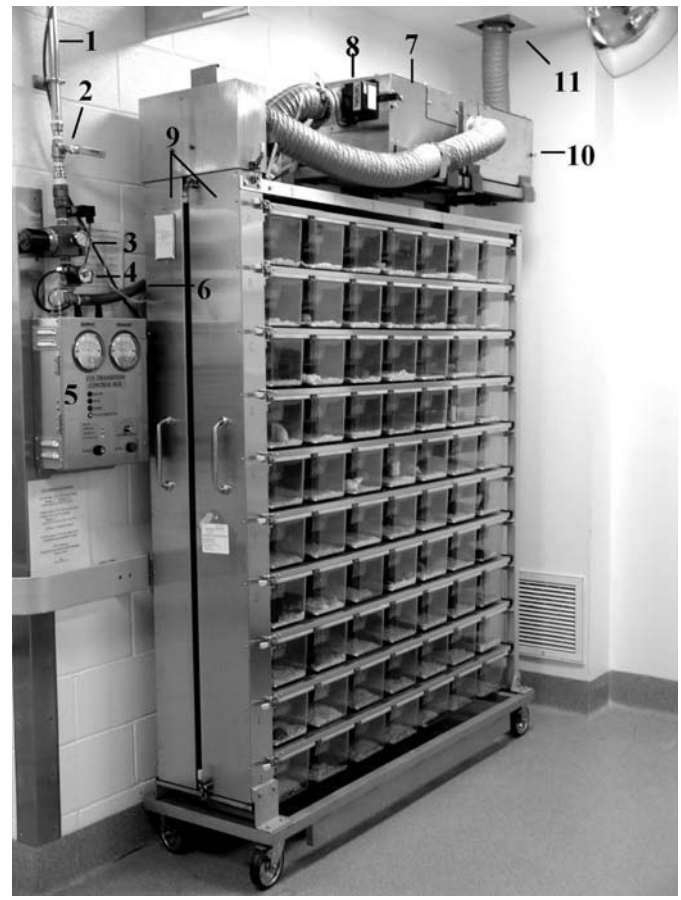


Fig. 20-14 Automated individually ventilated rack system for euthanasia: 1, building CO_2 supply; 2, manual ball valve; 3, high-pressure regulator; 4, solenoid-controlled female-valved coupler; 5, CO_2 transition control box; 6, high-pressure CO_2 hose; 7, supply blower; 8, motorized gate damper; 9, supply and exhaust plenums; 10, exhaust blower; and 11, thimble connection. Reproduced from McIntyre *et al*. (2007).

on room ventilation to provide sufficient supply air for the system to ensure adequate fresh air and provide MiE temperature and humidity control. Typically, a minimum of 10–15 room air changes per hour are provided.

The advantage of this integration method is its simplicity, as there are no restrictions on rack placement other than access to electrical power; MaE particulate counts are reduced; MiE temperature and humidity control are straightforward as they are dependent upon MaE conditions; and blowers may be integrated by the manufacturer such that failure of either the supply or exhaust blower will result in shutdown of the opposing blower. The disadvantages of this integration method include the need for electrical power (emergency power preferred) and outlets to serve the supply and exhaust blowers on each rack; the additional costs associated with the purchase and operation of the blowers; the MaE cooling required to counter the additional heat load generated by the blowers and the latent and sensible heat loads generated by the animals which

TABLE 20-1

ADVANTAGES AND DISADVANTAGES OF METHODS AVAILABLE FOR INTEGRATING VENTILATED CAGING INTO ANIMAL FACILITIES

	Method			
	Room supply/ room exhaust	Room supply/ direct exhaust	Direct supply/ direct exhaust	Direct supply/ room exhaust
Advantages				
lmproved intracage ventilation	X	X	X	X
Protective air pressure differential	X	X	X	X
Protection from macroenvironmental particulates	X	X	X	X
Protection from volatiles			X	X
Reduction in volatile release		X	X	
Reduction in particulate/allergen release	X[1]	X	X	X[1]
HVAC economy		X[2]	X	
Disadvantages				
Building HVAC system more complex		X	X[3]	X
Increased equipment costs	X	X	X	X

From Lipman (1993).
[1]If dedicated exhaust provided with HEPA filtration.
[2]Greatest economy achieved.
[3]Most complicated system.

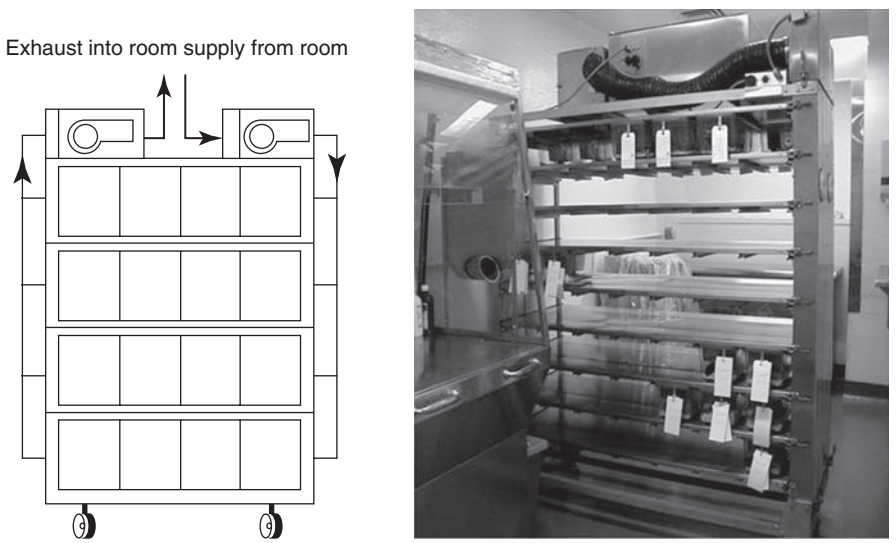


Fig. 20-15 Schematic and photograph of an individually ventilated cage rack in which supply air is drawn from the room and exhaust effluent is returned into the room. Photograph contains an IVC rack with top-mounted blowers.
Schematic courtesy of Phoenix Corporation, Inc.

are released back into the room; the noise associated with the blowers; vibration from blowers unless installed on the wall or on a rack independent of the cage rack; the reduction of indoor air quality as cage effluent containing volatile substances not removed by HEPA filtration is released back into the room; the acquisition costs for both the supply and exhaust blowers; and the costs, time, and effort required to operate and maintain the blowers.

Room supply/direct exhaust system In this configuration room air is drawn through a blower, filtered, and directed into individual cages. Subsequently, the rack's exhaust system collects cage effluent and releases it directly into the building's exhaust system. There are two options for exhausting the ventilated rack: (1) the building's exhaust system can be used to produce the necessary static pressure and airflow (Figure 20-16), or (2) the rack(s) can be equipped with an exhaust blower(s) (Figure 20-17). HEPA filtration of the exhaust is generally unnecessary as the exhaust effluent does not re-enter the room, but the author recommends coarse (>30 percent) filtration to prevent build-up of debris in the building's exhaust system. Since cage effluent does not re-enter the room, the quantity of air necessary to ventilate the holding room and provide sufficient air to meet the supply requirements of the caging system is frequently less than the 10–15 air changes per hour typically provided to animal holding spaces. In this integration method,

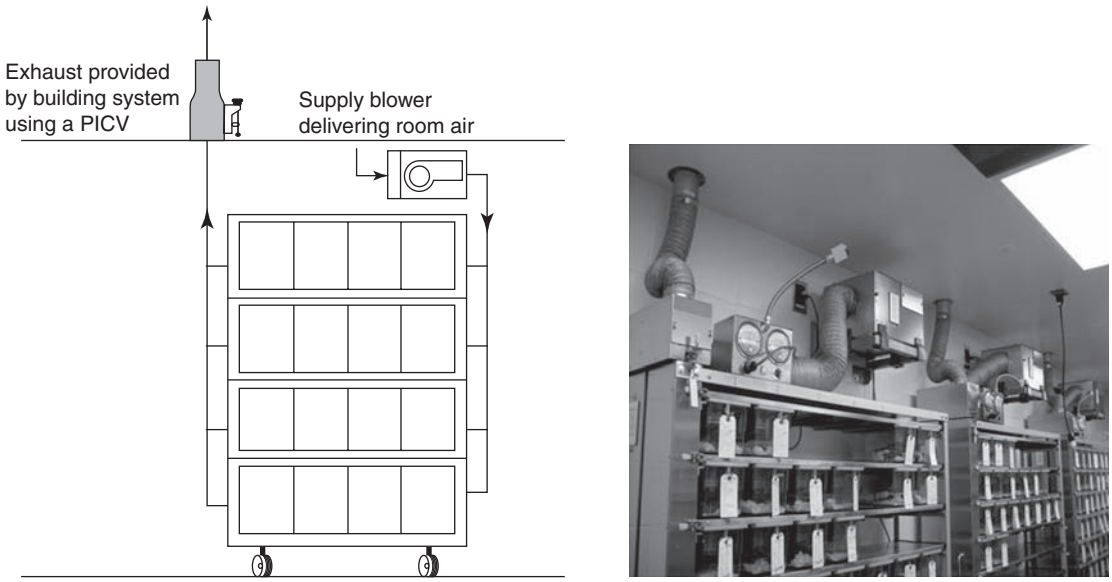


Fig. 20-16 Schematic and photograph of an individually ventilated cage rack of the room supply, direct exhaust type. In the system shown, exhaust is provided by the building's system and therefore, no rack exhaust blower is provided. Exhaust stability is ensured with the use of a PICV.
Schematic courtesy of Phoenix Corporation, Inc.

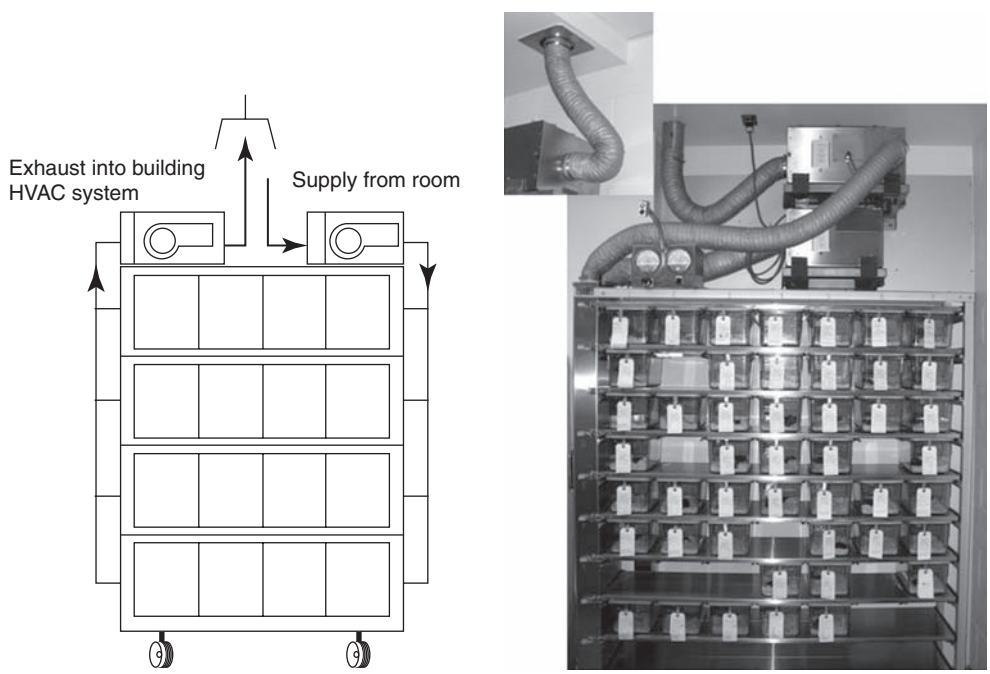


Fig. 20-17 Schematic and photograph of an individually ventilated cage rack of the room supply, direct exhaust type. In the system shown, exhaust is provided by an exhaust blower on the rack and delivered to the building's exhaust system through a direct connection. A thimble connection (inset) can also be used.
Schematic courtesy of Phoenix Corporation, Inc.

the room can be considered an extension of the HVAC supply, as no or minimal contaminants should return to the room from the cages. Ventilation rates could be reduced to as low as 8 ACH, the level provided for general laboratory space (National Research Council, 1981; ASHRAE, 1991). The heat load generated by the animals, personnel, equipment and lights will dictate the minimal ventilation rate. This ventilation rate must ensure adequate MaE temperature and humidity control, and provide a comfortable environment for personnel. Cooling requirements are significantly reduced with this method, as

Fig. 20-18 A venture-type PICV. The knob on the top of the device is used to adjust the volume of air provided by the device within its design specifications.

Reproduced courtesy of Allentown Caging Co., Inc.

a considerable component of the animal- and blower-generated heat load is released directly into the building's system and does not re-enter the room. Reducing room ventilation rates can translate to significant operational cost savings as energy costs for conditioning and moving air are reduced and, when integrated into new construction or renovation plans, may allow for additional savings if downsizing of air-handling and -conditioning units are considered. The ventilation economy gained from this installation frequently exceeds all other integration methods.

Although there are significant advantages of a room supply/direct exhaust installation, its limitations should be considered. The room exhaust system is considerably more complex because specialized exhaust manifolds equipped with dampers or thimble connectors are required, and if a room-based blower system (described below) is also employed then the supply system is similarly complicated. As a result, first costs are considerably higher as compared to a room supply/room exhaust system. Building exhaust duct pressure fluctuation is a concern and must be tightly controlled, especially if using the building's system (in lieu of a rack blower) to exhaust the rack. If not using a rack blower, ideally the exhaust drop to each rack is equipped with a pressure-independent, constant-volume device (PICV), such as a venturi valve (Figure 20-18), which is balanced to meet the exhaust requirement of the individual rack. However, PICVs capable of precisely maintaining low air volumes (<30 cfm) are not available, which may require (dependent upon the rack's design and cage capacity) multiple racks to be controlled by a single device (Figure 20-19). In this case, racks may require careful and often frequent balancing and/or the use of load simulators (Figure 20-20). Load simulators, which are simple devices that mimic the pressure drop across the rack, ensure that a drop in static pressure does not occur in the exhaust ductwork served by the same PICV when one or more racks are removed from the system. If a load simulator is not utilized the exhaust to the racks remaining on the circuit will be reduced, as a greater volume of air will flow through the open exhaust connection because there is less static pressure between the exhaust duct and the room.

If exhaust blowers are provided, they are accompanied by the increased cost of acquisition, operation and maintenance, as well as noise; however, the caging system is not dependent on the building's system to ensure proper rack function as long as the system is designed and operated properly. If exhaust blowers are directly coupled to the building's exhaust, a method must be employed to ensure fluctuations in duct pressure do not impact rack operation. This can be accomplished in several ways. A thimble connector (Figure 20-17 inset) can be utilized and/or the rack and room exhaust can be placed on the same duct run, preferably served by a PICV, set to exhaust air at a volume greater than the racks combined (Figure 20-21). In this scenario, the exhaust register in the room serves to accommodate changes in duct pressure, exhaust-blower volume, or both.

As with rack exhaust, there are also options for supplying air to the racks: either each rack can be provided with its own independent blower and filter assembly, or all racks in the holding room can be served by a room-based blower and filtration system (Figure 20-22). In the latter case, room air is extracted utilizing a fan which then directs the air into a duct distribution system supplying each rack in the room. Because the discharge temperature in the immediate vicinity of the supply diffuser fluctuates considerably as a result of changes in reheat coil operation, air should not be extracted in its vicinity. As supply air provided to IVCs is generally HEPA filtered, a filter assembly is usually accommodated downstream of the blower. Although the supply air is HEPA filtered, volatile substances present in the room would not be filtered and would be directed into the cages. As the system serves multiple racks, blower redundancy is recommended. Although manual dampers can be used to control the air volume provided to each rack, a PICV, serving each rack, is preferred to ensure a constant supply air volume and to avoid the need for frequent system rebalancing when rack occupancy changes and/or when racks are removed from the system. Depending on the IVC design and rack size, PICV may not be available which can accurately provide the required (small) volume of air needed. In this condition, multiple racks may need to be serviced by a single PICV (Figure 20-19). Rack simulators are employed, as previously described, to avoid changes in supply airflow when racks are removed from the system. Environmental control and monitoring are straightforward when the room is used as the supply air source, as the MaE conditions within the room closely reflect those occurring within the cage.

Direct supply/direct exhaust system In this configuration, racks are connected directly to the building's supply system

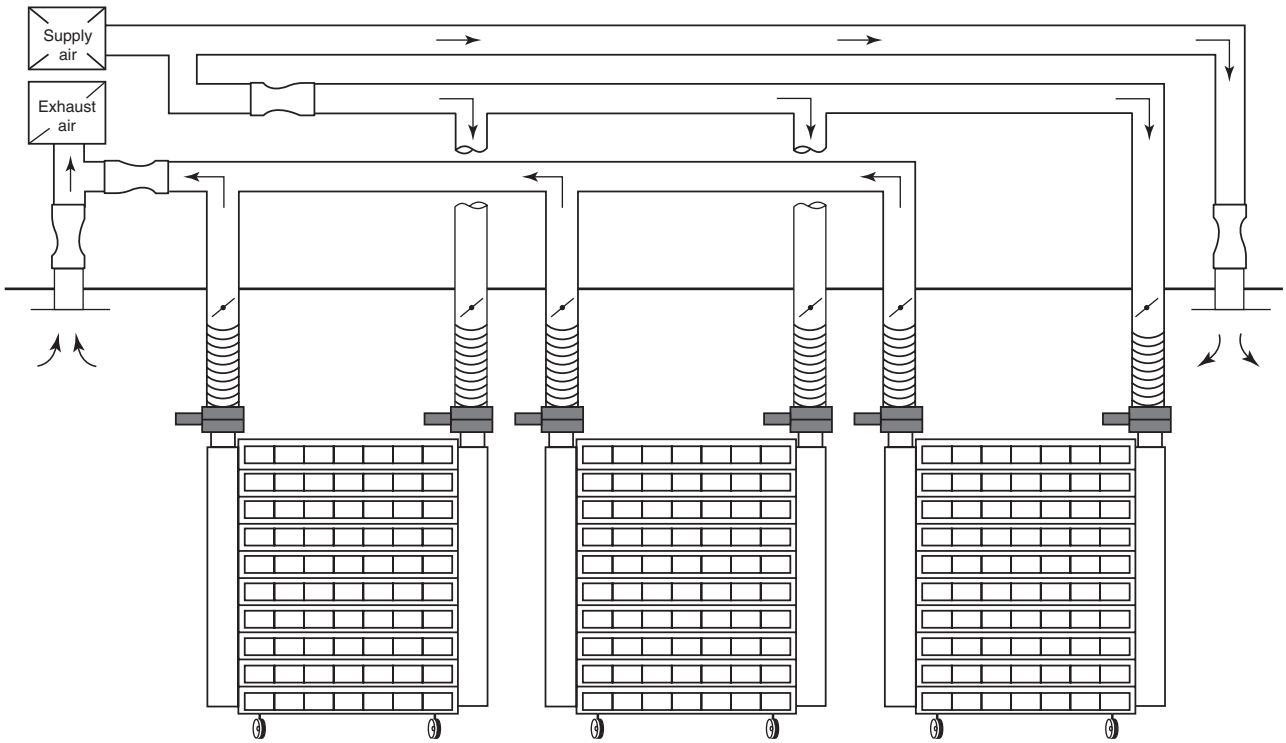


Fig. 20-19 Schematic depicting the installation of multiple individually ventilated cage racks of the direct supply, direct exhaust type. Multiple racks are served by a single PICV.

Reproduced courtesy of Phoenix Corporation, Inc.

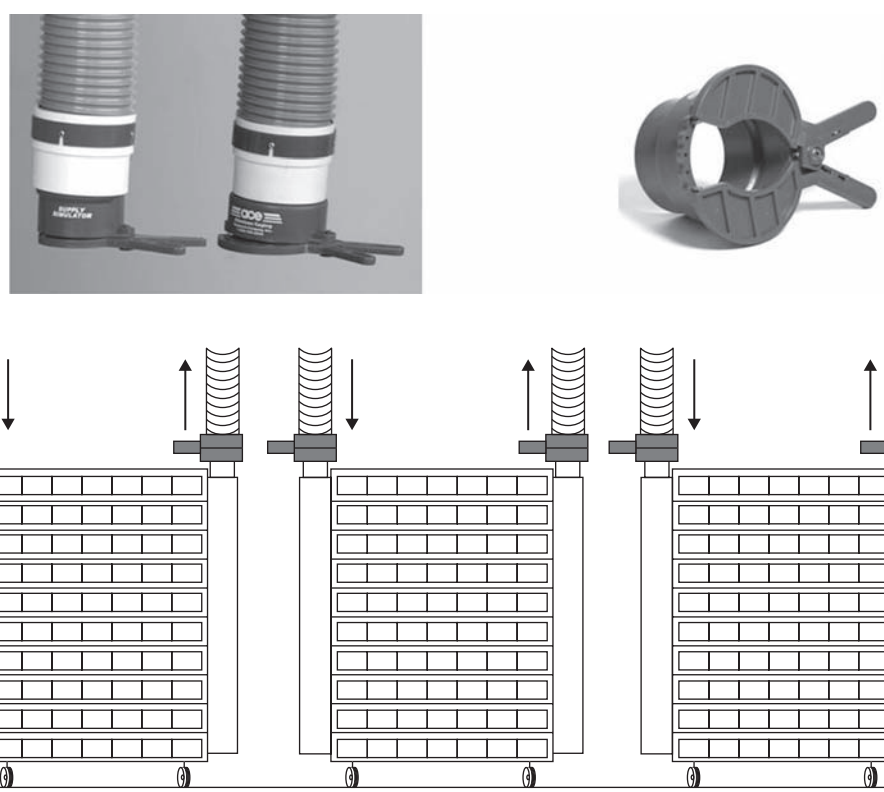


Fig. 20-20 Schematic of multiple individually ventilated cage racks equipped with load simulators. Spring-activated load simulators (insets) return to a specified position, decreasing the lumen diameter, mimicking the static pressure of a rack when the rack is disconnected from the system.

Insets courtesy of Allentown Caging Co., Inc; schematic courtesy of Phoenix Corporation, Inc.

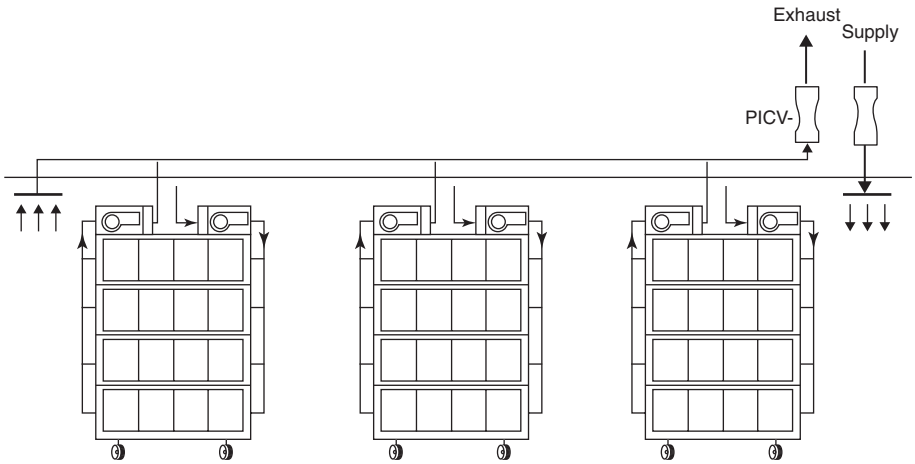


Fig. 20-21 Schematic of room supply, direct exhaust individually ventilated cage racks in which the exhaust blowers are direct connected to the building's system. The exhaust duct into which the racks empty effluent also provides room exhaust. The duct is served by a single PICV set to meet the exhaust requirement of all the racks in addition to the room. Changes in individual rack exhaust volumes which may occur are offset by changes in the room exhaust volume.

Modified from a schematic courtesy of Phoenix Corporation, Inc.

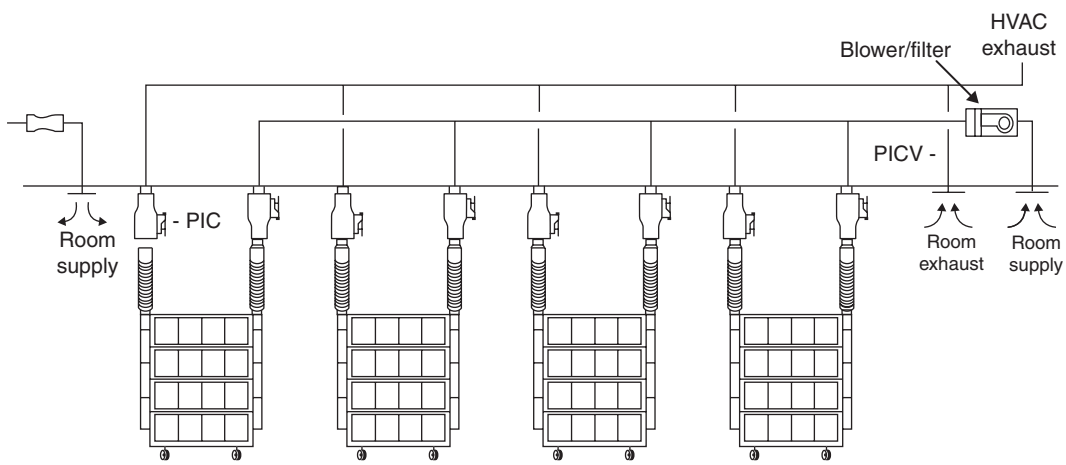


Fig. 20-22 Schematic depicting multiple individually ventilated cage racks of the direct supply, direct exhaust type. Each rack is equipped with (two) PICVs, ensuring appropriate supply and exhaust volumes are provided. In this scenario, supply air is extracted from the room and distributed to the supply side of the racks.

Schematic courtesy of Phoenix Corporation, Inc.

and rack effluent is subsequently exhausted directly into the building's exhaust (Figure 20-12). This method also allows the holding room to be ventilated at a lower rate. As described for room supply/direct exhaust systems, ~8 air changes per hour are generally sufficient to maintain MaE conditions and provide a comfortable and healthy work environment for personnel. With this method, IVC ventilation is completely independent of the holding room such that neither particulates nor volatile agents released in either the MiE or MaE will contaminate the other.

Although not essential, this integration method can utilize the building system in lieu of a rack supply and/or exhaust blower to avoid the associated cost, utility and maintenance issues associated with blower use. If building systems are utilized, this integration method offers a marked reduction in MaE noise as rack blowers are not employed. Additionally, there is no requirement for power to serve blowers, and nor are there issues relating to blower operation and maintenance.

The considerations discussed above with respect to direct exhaust, e.g., airflow volume limitations of PICV, are also applicable to both the direct exhaust and direct supply sides of the system. The principal disadvantages of direct supply/direct exhaust systems are the considerable costs associated with the additional ductwork, both supply and exhaust; the associated HVAC equipment required; as well as the difficulty controlling and monitoring MiE environmental conditions. There is also an increased risk associated with environmental control if the supply system should fail. If the racks are not provided with independent blowers, loss of either supply or exhaust ventilation results in loss to all racks connected to the system and, as there may be no operational connectivity between the supply and exhaust systems, loss of either dramatically alters intra-cage pressure. In contrast, manufacturer-supplied blowers may be integrated so that if one fails the opposing blower automatically powers down/off to ensure that the desired intra-cage pressure is maintained or, at worst, becomes neutral.

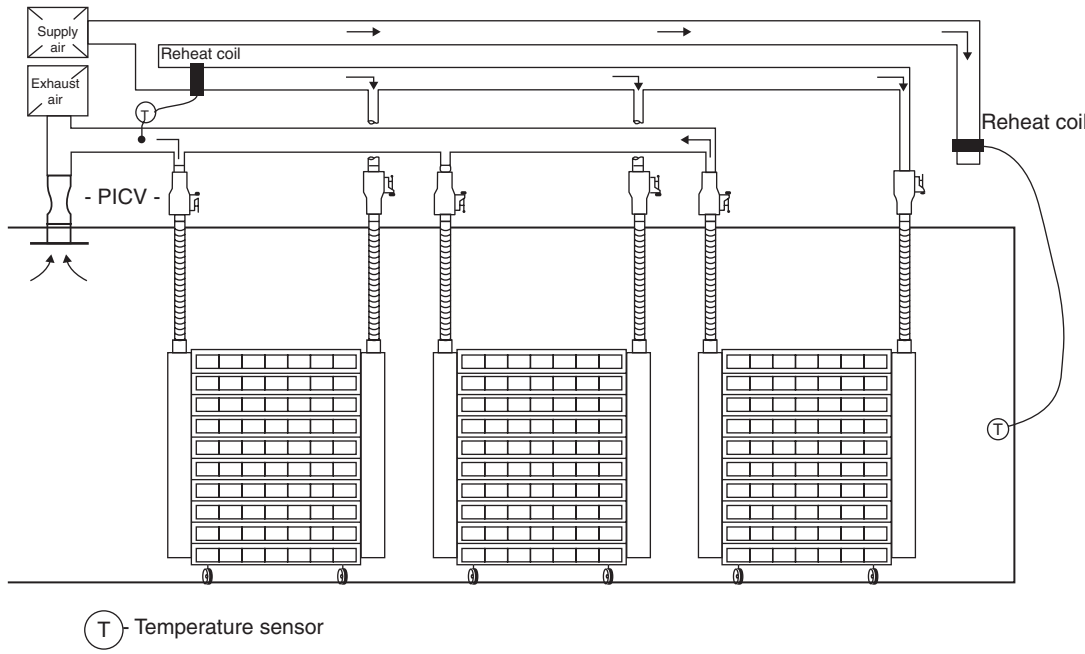


Fig. 20-23 Schematic of individually ventilated cage racks of the direct supply, direct exhaust type. In this scenario supply is provided by the building's system. Supply air temperature to the racks is controlled by a dedicated reheat coil distinct from the coil controlling room temperature. The valve position on the coil serving the rack is determined by a temperature sensor located in the exhaust duct serving the racks.
Schematic courtesy of Phoenix Corporation, Inc.

As with direct exhaust, the racks can be supplied directly from the building's supply air system by providing ducts as well as an independent temperature loop similar to (but distinct from) that provided to the holding room (Figure 20-23). This method is considerably more complex than utilizing the room as the supply air source. Although this concept has been used successfully, it is accompanied by a number of potential pitfalls. The principal advantage with this method is that it provides the ability to maintain MiE temperature and humidity at levels distinct from those in the MaE. However, maintaining and monitoring MiE conditions, which are not directly perceivable to personnel, is difficult, and may reach critical levels before identification. It is challenging to determine the ideal location for placement of the temperature sensor feeding back to the reheat coil controlling supply air temperature. Although there are several options, the most feasible is to monitor the air temperature in the exhaust duct into which effluent from the IVCs is exhausted. This method does not account for heat load differences which may occur in individual cages with different numbers of occupants and, more importantly, exhaust may be diluted significantly with room air in some IVC systems such as direct supply/perimeter capture racks. Therefore, placement of additional temperature sensors in the supply ducts, in proximity to the racks being served, is recommended to monitor rack supply air temperature. In addition, HEPA filters, which are commonly employed, are frequently placed a considerable distance away from the racks with extensive, potentially contaminated, ductwork downstream of the filter. The HEPA filter imposes additional demands on the ventilation system by creating resistance which must be overcome by providing air at an increased static pressure. As the filter loads, the static pressure required to overcome the increased resistance of the filter also rises. To provide increased static pressure, the building's blowers must provide more air, which increases energy utilization and wear and tear on the equipment. Placing filters in close proximity to the racks (e.g., at the holding room) can significantly reduce the length of contaminated duct; however, the system must overcome the static pressure of the most heavily loaded filter in the system. Consequently, the author recommends using a blower and HEPA filter on the rack, which extracts air from the supply duct. The increased static pressure required for individual filters will be compensated by the respective rack's blower, and will not impede the building's system. Energy consumption will be less because the individual blowers on the racks are considerably smaller and more efficient than those used in the building's systems. In addition, access to filters for cleaning, changing and testing is easier when the filters are located on the rack.

Direct supply/room exhaust system A direct supply/room exhaust system consists of providing supply air directly through a duct from the building's HVAC system. The air is then supplied to individual cages through the rack's air distribution system. Exhaust air is filtered before dumping it back into the holding room. Although this installation method is theoretically possible, it provides no advantages. Although

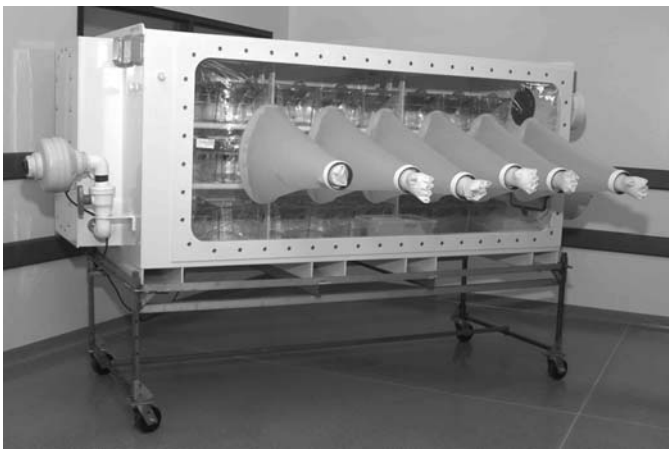


Fig. 20-24 Semi-rigid isolator containing both rigid (polypropylene) and flexible (polyurethane) plastics.
Reproduced courtesy of Charles River Laboratories, Inc.

Fig. 20-25 Multiple portable, positive-flow/pressure, flexible-wall, vertical-flow MAD rooms for mouse holding and breeding.
Reproduced courtesy of Taconic Farms, Inc.

volatile materials released in the holding room will not contaminate the micro-environment of the animal's cage, volatile intra-cage contaminants such as ammonia will be released back into the room.

3. *Isolators*

The first rigid stainless-steel isolator was developed by Reynier for the production and maintenance of gnotobiotic rodents. Isolators continue to be an important husbandry resource, as they provide complete physical separation between the animals housed within and the surrounding environment. They are used for biohazard containment as well as for maintaining axenic, gnotobiotic, adventitious agent-contaminated and/or immunocompromised rodent lines or stocks. Most rodent production facilities maintain and breed foundation stocks and immunocompromised lines within isolators.

Modern isolators are either of the flexible type, generally manufactured of polyvinyl chloride (PVC) or polyurethane, or semi-rigid, a combination of both rigid (polypropylene) and flexible plastics (Figure 20-24). Although, historically, isolator supply and exhaust air was filtered through fiberglass floss media, modern units employ HEPA filters. The principal disadvantage of isolators is that they are operationally intensive.

4. *Mass Air Displacement Units Including Changing Stations and Biological Safety Cabinets*

Various types of equipment employing HEPA filtered, laminar flow, mass air displacement (MAD) were developed in the late 1970s for animal holding, and subsequently for cage-changing and animal manipulation. Although many MAD housing designs have been made obsolete by IVC, a number of commercial systems are available and have applications today in specialized settings. MAD units designed for cage-changing and animal manipulation are rapidly becoming the standard of mouse husbandry throughout the US.

MAD (or clean room) technology originated from industries requiring dust-free environments for manufacturing. During the 1970s, the technology was adapted for use in animal research facilities. MAD units are available to operate in either a positive or a negative mode, providing either product (animal) or personnel (containment) protection, respectively. Operated in a positive mode, a fan supplies large quantities of HEPA filtered air into a plenum and subsequently through a perforated panel, creating unidirectional laminar airflow bathing the materials to be protected. Although the airflow pattern is laminar at the source, it is disrupted by objects in its path and the pattern is lost as the air moves farther away from the source. Units developed for animal research typically are of the Class 100 type. Class 100 air is defined in the Federal Standard No. 209E as filtered air that contains no more than 100×0.5-micron particles or larger per cubic foot of air (Code of Federal Regulations, 1992). Negative flow units provide containment as they draw large quantities of air over animals, HEPA filtering the exhaust effluent before its release into the environment. A further distinguishing feature is whether the air moves vertically (i.e., whether it is delivered/collected from above the cage) or horizontally (in which case it is delivered/collected across the cage).

MAD units include fixed or portable, solid- or flexible-wall cubicles or rooms. Using these units, barrier-level animal holding rooms can be established in large open spaces in which environmental control can be simplified and construction costs reduce.

Figure 20-25 details an example of a facility employing multiple portable, positive-flow, flexible-wall, vertical-flow

Fig. 20-26 Portable horizontal flow mass air displacement unit for cage-change and animal manipulation.
Reproduced courtesy of Nuaire, Inc.

MAD rooms for rodent holding and breeding. Similarly, negative-flow, portable MAD cubicles can be set up to segregate shipments (e.g., quarantine of distinct rodent lines) or, if operated in a negative-pressure mode, can be used for biocontainment. MAD units can be used to create air locks within established hard-walled rooms or to collect aerosols during waste dumping.

Positive-flow MAD units are commonly employed for cage-changing and animal manipulation. In the author's opinion, vertical flow units, most of which attempt to capture and subsequently filter effluent before release, are generally preferred to horizontal units, which release larger quantities of particulate into the MaE. Horizontal units are typically tissue culture hoods that have been adapted for use in the animal facility (Figure 20-26). Horizontal units have ergonomic advantages, because of their large, open work area, and can be purchased so that they are height-adjustable. However, neither vertical nor horizontal flow units should be used with biohazardous agents, and both have the potential of increasing personnel exposure to allergens. The newest changing-station designs are based on vertical flow, and are open for access on either two or three sides. These units can be used by more than one person simultaneously, are height-adjustable, and have a perforated work surface to capture (some) effluent that is HEPA filtered before release (Figure 20-1). Some facilities operate change stations continuously to filter room air, reducing particulates. It is important to note that cage-changing techniques must be adapted to the unit type – horizontal or vertical – as the direction of airflow dictates the preferred plane and manner in which clean and soiled materials are handled. Also, changing stations that provide only product protection should never be used with biological hazards.

Although there is no prescribed regulatory requirement for assessing the function of MAD units, a professional certifier should be retained to confirm that filtration meets the Class 100 standard. At the author's institution, MAD equipment is tested and certified at least annually.

BSCs are frequently used in the vivarium. They are classified as Class I, II or III, based on their operational design (Wilson and Chosewood, 2007). Class I cabinets provide personnel protection only. Their use in animal facilities is limited to bedding dump stations.

Class II cabinets, which provide both product and personnel protection, are used for animal and material handling when BSL-2 and -3 agents are used. There are four types (A1, A2, B1 and B2) of Class II BSCs. Air is recirculated in Type A1, A2 and B1 cabinets. Effluent from A1 and A2 cabinets may be released into the MaE or connected to the building's exhaust through a thimble connection. Many facilities use Class II Type A cabinets for routine cage-changing, because of concerns relating to allergens. Type A cabinets have been adapted for cage-changing and animal manipulation by increasing the sash height to allow movement of MIs into and out of the cabinet without disturbing the lid, and may be mobile, height-adjustable and equipped with a variety of options, including pass-through waste disposal ports, and feed-, water-, and cage-delivery systems (Figure 20-2).

Type B cabinets must be hard-connected to the building's exhaust system, have 100-lfpm face velocity, and negative-pressure plenums, making them suitable for use with toxic chemicals and radionuclides. Type B2 or 100 percent exhaust cabinets do not recirculate air and therefore are preferred when using highly toxic volatile chemicals, although the quantity of chemical used may need to be limited to avoid degradation of the HEPA filter. When used for the containment of hazardous agents, Class I and II cabinets must be certified to meet National Sanitation Foundation International (NSF) Standard 49 upon installation, whenever they are moved, and at least annually (National Sanitation Foundation, 2002). Mobile units that are used for cage-changing and animal handling but not for hazardous agent containment should be certified at least annually. Units used for hazardous agent control should be certified each time they are moved.

The use of Class III cabinets, which provide the highest level of containment suitable for organisms requiring BSL3

and -4 containment, is highly specialized and beyond the scope of this chapter. Wilson and Chosewood (2007) should be consulted for additional information.

III. CONCLUSION

The sophistication, complexity and size of research facilities that support rodent model development and use continues to escalate. Academic and industrial biomedical research institutions typically maintain tens of thousands of rodent cages. In addition to providing stable environmental conditions that minimize physiological perturbations, which may affect research results, animal research facilities must be designed and operated with optimal productivity and efficiency. Caging systems that directly ventilate the MiE to which the animals are exposed are now routinely employed. Ventilated changing stations and BSCs have also become an essential component of the animal holding room for both cage-changing and animal manipulation. The use of robotic technology to perform routine husbandry tasks, an area that has recently emerged and continues to evolve, is expected to expand. As a result of these changes, research animal facility professional and management staff, as well as architects and engineers specializing in vivarium design, must have a thorough knowledge of and keep abreast of a broad array of issues relating to mechanical, caging, and environmental monitoring systems. Additionally, these professionals should be attuned to operational processes, ensuring that newly-constructed facilities operate at the highest level of efficiency while allowing generation of the highest-quality research data.

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Chapter 21

Facilities for Non-human Primates

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I. INTRODUCTION

Facilities that house non-human primates (NHP) incorporate many of the same design features as housing facilities for other laboratory animal species. Recognition of the specialized needs of NHP species is critical to the incorporation of design features that will streamline daily operations in these facilities by providing for a safe environment for personnel, as well as opportunities for the provision of environmental enrichment for NHP. This chapter focuses on specific design and construction features of NHP housing facilities, with descriptions of both indoor and outdoor housing structures. The design criteria discussed in this chapter conform to the standards and guidelines of the *Biosafety in Microbiological and Biomedical Laboratories*, 5th edition (the *BMBL*; CDC/NIH, 2007), *The Guide for the Care and Use of Laboratory Animals* (the *Guide*; ILAR, 1996), and the Animal Welfare Act (AWA). In addition, the facility must comply with all applicable national, regional and local building codes.

Considerations for the design of facilities housing NHP should include species-specific behavior as well as the requirements for increased space, waste production and biosafety (Kelley and Hall, 1995). Ergonomics is a critical consideration, since many husbandry practices in NHP facilities require lifting heavy equipment or other strenuous activity. Since most configurations for indoor NHP housing result in open, stainless-steel wire cages as the primary enclosure, the animal housing room can be considered an extension of the primary enclosure with regard to containment of infectious agents. Because of the open nature of the cages, all exposed surfaces in NHP holding rooms should be considered contaminated and should be cleaned regularly as part of the husbandry program. Construction details and finishes must be enhanced to withstand these daily cleaning procedures, which are performed on all exposed surfaces within the housing room.

If all or a portion of the facility is to be funded by the National Institutes of Health, all space requirements for NHP facilities should follow the space standards and recommendations as set forth in the NIH Design Policy and Guidelines for both laboratories and vivaria, as well as the AWA and the *Guide*. Appropriate performance standards should be used in conjunction with design standards in the operation of NHP facilities.

The descriptions of facility design and construction in this chapter are focused on housing non-human primate species. Research facilities that house primarily non-human primates are limited compared to facilities housing multiple species. The scope of this chapter does not allow the discussion of the construction of non-human primate housing facilities that are able to accommodate a large variety of laboratory animal species interchangeably. It is hoped that readers will be able to utilize the information presented in this chapter to determine the minimum design standards necessary to house non-human primates. If necessary, additional design criteria can be developed that would allow the housing of other species in the same space. The reader is referred to other chapters for further non-primate species-specific construction information.

II. GENERAL CONSIDERATIONS

A. Site Planning

When planning the construction of a new NHP facility, particular attention should be paid to site location. These facilities should be isolated from spaces housing other species, since NHP generate significant noise (ILAR, 1996). Husbandry procedures such as cage-changing and cage-washing also contribute to significant noise generation, which could be detrimental to the well-being of other laboratory animal species. If program requirements mandate that NHP be located in close proximity to other species, efforts should be made to isolate NHP through the facility design and construction. This may include the use of double doorways with anterooms. In so doing, a sound transmission buffer is provided between areas of high noise-generation and low sound requirements. In addition, corridors should be isolated to minimize the movement of more than one species through them if possible.

For outdoor or indoor/outdoor housing, it is important that a perimeter buffer zone be present to decrease the levels of noise and odors from impacting neighbors of the facility. These buffer zones could be composed of a natural landscaped buffer zone, a rigid wall-type buffer zone, or a combination of both. Outdoor and indoor/outdoor facilities should be located within a secure area, because these facilities are, by their nature, less secure than indoor facilities.

Site planning should take into consideration the location of centralized support service facilities such as necropsy, radiology, surgery and waste-processing. Most indoor NHP facilities are operated using ABSL2 containment practices to prevent exposure of untrained or unprotected personnel to NHP and/or their wastes. The distance required to transport NHP from housing facilities to centralized support service facilities must be minimized and limited. This should be accomplished primarily through thoughtful site planning, and secondarily by the use of standard operating procedures. Within a single facility, this can be achieved using performance standards that designate specific times for use of shared facilities by NHP or specifically designating areas for NHP use only. The use of anterooms and airlocks is helpful in this regard.

Housing facilities should be located in close proximity to access roads to allow for transport of food, caging and other large equipment by vehicle. Quarantine facilities requiring frequent transport of large numbers of NHP should be sited in close proximity to access roads sufficient in design to support the access of large delivery trucks, yet far enough away from permanent holding facilities to prevent potential cross-contamination from newly imported animals.

B. Environmental Enrichment

The provision of environmental enrichment to promote psychological well-being, which is mandated by federal law, is an important consideration during the design phase of an NHP housing facility (ILAR, 1996; NRC, 1998). Consideration should be given during the design of the facility to include the versatility necessary to provide for social housing, which is considered one of the most important efforts to provide behavioral health in NHP. Social housing may be accomplished in several ways. In indoor facilities, it is most commonly accomplished through caging configurations that permit group housing. Such caging configurations are often taller than single holding cages. Therefore, interior cage-transport routes and cage-processing equipment must account for the increased height. Door openings and ceiling heights must be verified with cage dimensions to ensure clear passage. Other environmental enrichment considerations may include provisions for manipulanda (toys) and food-related enrichment as part of the enrichment program, and may not have direct design implications over and above the need for additional storage space and sanitation requirements for these items.

Floor-drain or trench covers may be needed to prevent enrichment items from obstructing the sanitary sewer system. In addition to stainless-steel caging in animal housing rooms, social housing can be provided in a variety of different ways, using complex pen enclosures in indoor facilities, indoor/outdoor runs, or various-sized outdoor field cage/corral housing. Thought should be given to providing group housing for different sizes and ages of animals, increasing the versatility of the housing area. In most cases, animal housing rooms should be designed to allow NHP to see, smell and hear other animals in the room. When this is not possible due to space constraints, mirrors can be mounted on the wall in front of a single row of cages to allow animals to visualize others in the room (NRC, 1998). Facilities used for nursery rearing should have the capability to provide space for singly housing very young neonates, along with several areas that offer the ability to socialize in progressively larger groups as the animals age. This can be accomplished by using a combination of indoor facilities for younger animals with larger group housing performed in runs, which incorporate indoor/outdoor components.

More information related to the provision of environmental enrichment can be seen in the sections describing the construction of specific facility components.

C. Waste Management

Non-human primates typically generate large amounts of fecal and food waste. NHP will commonly hide food material inside and outside of the cage. Because of this behavior, NHP housing rooms should be designed to allow additional space around rolling cage-racks to accommodate movement on a daily basis for cleaning. It is common to attempt to maximize the number of animals held in a given space, thus decreasing the amount of room that is available around cages for sanitation. It is prudent not to completely fill rooms with caging, as this practice results in more difficulty and time required for cleaning.

Because of the biosafety issues involved with NHP, large amounts of personal protective equipment (PPE) are required. Therefore, the storage, transport and disposal of such material should be considered in the design of such facilities.

The number of carcasses processed daily depends on the number of animals in the colony and the type and size of the research program. Since most species of NHP used in research are of considerable size, the disposal of NHP carcasses or storage until transport for third-party disposal must be considered during the design phase of construction projects. Since NHP carcasses are considered biohazardous, secure storage area must be available if they are to be stored prior to final removal. Many facilities store carcasses close to onsite incinerators or tissue digesters, which are used for final processing. Storage sites for carcasses should be secure, and in an area with containment protocols in place.

D. Pest Management

As in other facilities housing laboratory animals, NHP facilities must be constructed to minimize vermin infestation. Of particular concern for NHP is the volume of food waste that is generated daily as a consequence of normal foraging behavior in these species. In addition, the behavior of NHP and the types of complex caging systems used permit the hiding of unused food inside and outside of cages. Floor drains and troughing, if not cleaned adequately, can contain waste food material, which is attractive to pests.

Attention should be given during the design phase to provide areas and finishes that enhance and facilitate effective sanitation practices. Proper and frequent sanitation greatly decreases the waste present in NHP housing rooms, which results in less attraction for pests. Rolling rack cage systems are generally preferred because cages are more easily moved for cleaning than wall-mounted caging. Corridors should be wide enough to allow easy movement of caging to cage-washing equipment. Cage-wash facilities should be placed in close proximity to the housing building, and attached to the housing building if at all possible. All lighting fixtures, electrical, data communication, fire alarm and security system outlets and raceways should be sealed, including wire conduit. This effort assists in the prevention of vapor transmission and reduces vermin infestation.

E. Facility Security and Communications

Each facility should incorporate physical security and communications systems at the time of construction. Facility construction funded by government agencies has prescribed security requirements such as site security and the control of

movement, for both people and vehicles, onto and around the site. The specific requirements necessary to meet the appropriate government standards as outlined in various government memoranda and bulletins should be consulted when developing a security plan. Consideration should be given to hiring a consulting firm which specializes in security for containment facilities in the preliminary design phase of the project. Security technology and equipment are rapidly upgraded, and a firm specializing in the field can be of great assistance in keeping architects and end-users informed of the state of the art. A facility design plan, which addresses security issues, should not only provide for animal security but also enhance biosafety for personnel working at the facility, as well as the surrounding community.

Communications systems within facilities are critical for supporting husbandry practices and research by facilitating communication and the transfer of data between animal housing and procedure areas, and the rest of the institution. Ports for network connections should be placed in procedure rooms of NHP facilities to allow ready entry of animal husbandry and veterinary data into the centralized animal records database. Wireless systems have become popular because of the ability to move terminals to any location, including animal rooms, allowing real-time entry of data. Telemetry is being used to more accurately monitor physiologic and behavioral parameters in NHP, and provisions should be made to allow animal housing rooms to be connected to a centralized data collection site. Consideration for data security should be taken into account when wireless systems are to be used for entry of animal data, since these systems can be less secure than hard-wired interfaces. In higher containment situations, such as ABSL3, wireless headset radios may be necessary for communication between staff within the facility as well as to communicate to others outside the facility if an accident occurs. These units are particularly useful when personnel are required to wear forced-air respirators, which can generate considerable noise within the headcover.

As for most facilities, the first line of security in NHP facilities should be controlled-entry access points (CDC, 2007). These points include the control of personnel access at the building's primary entrance, animal room corridor entry doors, procedure room doors, storage rooms and each animal room entry door. Minimally, access should be controlled at the building entrance, with a single access point permitted to the animal area for the majority of personnel. Access to collect animal tissues and other items for research studies can be accommodated by allowing access to the exterior door that leads to an anteroom with another access-controlled door that is limited to essential personnel. Tissues and other samples can be passed from the animal areas using wall-mounted double-door pass-through boxes. Pass-through boxes should be large enough to accommodate a large sealed container with specimens. Exterior doors used for equipment movement should be access controlled from the inside, with no exterior hardware. Special attention should be given to comply with national and local building codes to ensure that emergency egress routes are maintained in considering security control points throughout the facility.

Typically, access is controlled by using some method of identification for entry. Several identification methods have been used, and include swipe card readers, proximity card readers and biometrics readers. Because NHP primate facilities at ABSL2 and ABSL3 containment require that objects brought out of housing areas not be exposed to the environment in containment, proximity card readers are particularly well suited, as they can be read through most protective clothing without the need for removing the card and exposing it to the contaminated environment. Additionally, biometrics readers such as an iris scanner can identify personnel without the need to carry an identification card, and can be read through most PPE.

Additional security can be provided by the use of video-monitoring equipment placed in strategic locations in corridors and outside animal holding and procedure rooms. Since controlled substances are used as pre-anesthetics, anesthetics and analgesics in NHP, secure lock boxes should be present in each animal-use area. Proximity card readers or punch keypads can be integrated into lock boxes, with additional layers of access-controlled entry to the room and video surveillance at the door.

In addition to providing security for unauthorized personnel from entering animal facilities, equal consideration should be given when designing NHP facilities to provide for security measures to limit animal escape. Non-human primates, by nature of their strength, intelligence and potential for transmission of infectious agents, pose significant risk to personnel in the event of an escape. Primary cage enclosures usually provide a number of locking mechanisms. In indoor facilities, security is further enhanced by design of the animal room door, corridors, anterooms and exterior doors. All animal room doors should contain a window, which allows personnel to observe the room for escaped animals prior to entry. Doors should be self-closing and open inward to help ensure that they remain closed after personnel complete necessary activities in the room, and prevent escaped animals from leaving the room. Exits from animal room corridors should consist of a two-door interlock system. In such systems, each door is electronically linked to the other, permitting only one to be opened at a time. This design effectively places three doors between NHP and non-animal areas. Further discussion of security for outdoor housing facilities can be found in the outdoor facilities section of this chapter.

F. Environmental Monitoring, Lighting, and Emergency Power

There are several manufacturers of environmental monitoring systems that provide comprehensive monitoring systems for communications, environmental monitoring and security.

Such systems have several advantages, which include decreased cost when compared to separate systems, centralized monitoring of all systems at once, and the ease with which additional units can be added if new construction or renovation takes place.

Interior illumination should be adequate for all activities, avoiding reflections and glare that could impede vision. Guidelines for lighting intensity in animal rooms can be found in the *Guide* (ILAR, 1996). The average foot-candle level for husbandry work should range between 75 and 100. Many factors can play in the amount of available light in a given space, including the reflectance level of the walls, floors and ceilings, and the amount of equipment within that might impede ambient light. Remote and secure programmable central lighting control systems and local timed override switches are preferred for lighting control in animal housing areas. The lighting systems can be controlled through the building automation system. Override timer switches should be present inside and outside of each NHP housing room to allow opportunities for immediate observation, if necessary, during dark hours. The timers should be variable, and turn lights off as a default after a specified time in case personnel should forget to turn them off after the observation period has ended. A two-tiered, variable light-intensity system can be used to provide additional light during the time that husbandry and cleaning practices occur, reducing in intensity when these duties are not being performed (ILAR, 1996).

Exterior site-lighting design criteria should utilize the Illuminating Engineering Society of North America (IESNA) foot-candle level requirements as stated in the *Practice Manual: Recommended Lighting for Exterior Environments* (IESNA, 1999). In addition, site-lighting criteria should be adopted to maintain safe light levels while avoiding off-site lighting and night sky pollution. Technologies to reduce light pollution include full cut-off luminaries, low-reflectance surfaces and low-angle spotlights. Night-time lighting for outdoor breeding facilities should take into consideration the need for the animals to experience specified dark hours each day in order to provide for proper reproductive parameters (ILAR, 1996). This can be accomplished with infrared lighting if required for security cameras. Once an intrusion alarm has been activated, additional lighting can then be turned on if necessary and cycled off when no longer needed.

Provisions should be made to include emergency and standby power to NHP facilities to meet the safety needs of personnel working in the facilities, and the needs of NHP being housed and the people in the surrounding community. Generator back-up power should be provided to all NHP facilities, and should be available 24 hours a day in case of power outage. Provisions should be made to have ample run-time from the generators in case power outages are prolonged. A dual fuel generator power system should be considered in the design of the building. Availability of supply fuel should be considered in determining the length of time emergency generator power should be provided to the facility. At a minimum, lighting and negative airflow (exhaust) should be preserved in NHP housing and use areas to maintain containment. In the best circumstances, both conditioned supply air and exhaust functions should remain operational on emergency power. Emergency power outlets, such as those used to provide life-support features, should be installed in designated areas during construction to ensure that specific critical functions (such as those required in surgical or intensive-care areas) are maintained when using generator back-up power.

III. INTERIOR CONSTRUCTION

A. Partitions

The exterior construction of NHP housing facilities may vary considerably depending on local site and planning conditions as well as desirable esthetic qualities. The interior construction of NHP facilities, however, must be designed to withstand the rigorous and harsh conditions inherent in a facility built to house and research NHP. Interior partitions must be rigid enough to withstand frequent movement of heavy racks, cages and other large pieces of bulky equipment. While metal studs and dry-wall construction may be sufficient for some small laboratory animal species, concrete masonry units (CMU) or concrete walls are preferred in NHP facilities to achieve the impact resistance required. Eight-inch minimum width CMU walls with struck masonry joints spanning the floor to underside of the structure at the perimeter of the facility should be used in corridors and cage-wash areas. Six-inch CMU walls with struck masonry joints at walls may be used to partition animal holding rooms, and procedure rooms, gowning and locker rooms, feed prep and staff areas. The cells of the CMU should be grouted solid to 5 feet above the level of the finish floor in walls that support troughing and/or secure NHP caging rack hold-down brackets. In so doing, anchors will have greater holding power as they engage the increased mass of the concrete. The height of the walls should extend to the underneath side of the structure above, to provide a clean separation between spaces and help prevent cross-contamination between rooms. Four-inch CMU walls with struck masonry joints may be provided to enclosed plumbing and ventilation chase conditions. These walls may extend to 1 foot above the ceiling height of rooms they are located within. All openings through walls above and below the ceiling should be sealed airtight. Penetrations through fire-rated assemblies must be fire-stopped in accordance with the fire rating.

B. Doors and Frames

Doors and frames in NHP facilities should be able to withstand daily disinfectant use and be resistant to damage if

involved in collisions with large equipment such as cage rack systems. Doors to animal rooms should open inward, and be self-closing for safety. Typical doors in animal, cage-wash and service areas can be fiberglass-reinforced plastic (FRP), stainless steel or galvanized steel, with smooth, flush surfaces without visible joints or seams on exposed faces or stile edges. FRP is preferable to galvanized steel, as it does not require painting, does not rust or dent, and can withstand daily use of cleaning chemicals. FRP doors are also lighter than metal doors, and less expensive than those made of stainless steel. Sizes of doors and doorframes can vary, but must be large enough to accommodate the passage of large caging racks that are housed in the room. Taller doorways are preferred, because many NHP caging systems are manufactured to allow enough vertical space for animals to climb. Service areas that do not require movement of NHP caging systems can have more conventional doorway widths and heights. Continuous, stainless-steel piano-type hinges are preferred due to their strength and durability. In addition, they help prevent warping of the door by providing increased support on the fastening side. Doors located on holding and procedure rooms should have a vision window measuring approximately 30 × 30 inches. The window should be covered with a shutter, which prevents light from entering the room from the corridor during dark hours (Figure 21-1). Windows should be located, sized and shaped appropriately so that staff of varying heights can easily view the room through the windows.

Fig. 21-1 Exterior view of animal room doorway.

All doors leading to NHP housing rooms should have a window in order to allow personnel to view the room prior to entering to provide safety in the event of an animal escape. The doorway should also have roller systems and bumper guards to prevent damage from collisions with large equipment. An airflow direction indicator can be seen in the upper left of the doorway and can be used by personnel to quickly assess containment breaches due to changes in airflow. Other items present at the entrance include a proximity card reader for access control and an override timer for the room lights.

Doorframes may be constructed of stainless steel or welded steel, hot-dipped galvanized, and finished with two coats of epoxy paint in order to reduce rusting. Knockdown frames should not be used because the seams and joints provide areas for the growth of bacteria and the harborage of vermin. Protection to doorframes can be provided by installing stainless-steel rolling bumpers on the edges of the frames.

The type of hardware installed on doors is critical to the security of animals and to the safety of personnel. Considerations for selection of door hardware should be the same as for other equipment in the facility, and include the ability to withstand repeated use and the use of harsh chemicals. It must be heavy duty in strength, and coordinated with the function for which it will serve. It is critical that door hardware be protected from inadvertent bumping when moving caging systems around the facility. Many bumper systems exist to accomplish this protection. Door stops should be placed on animal room doors and be used when moving equipment in and out of rooms.

To assist entry /exit to cage-wash facilities or other high-traffic areas, automatic power-operated double doors with wall-mounted, push-pad operators can be installed. This configuration facilitates in the movement of animals and/or equipment through these spaces.

C. Floors

Floors and the material placed on them are critical in day-to-day activities that occur in NHP facilities. Floors must be impervious to animal-waste fluids and the harshest cleaning and disinfectant chemicals. They must be impact-resistant, to hold up under the abuse associated with the movement of heavy racks and equipment. In addition, they must be slip-resistant when wet and be able to withstand the high temperatures and pressure of frequent hose-down. Concrete substrate with a troweled-in-place epoxy coating is an excellent product that satisfies each of these requirements. There are numerous floor-covering materials, other than epoxy, that also provide a smooth, seamless, impervious, impact-resistant surface. New materials are constantly being developed, and it is imperative that when choosing flooring substrates for NHP facilities that they have been previously evaluated under rigorous conditions. Rubber-mat flooring can be used in some wash or other

wet areas in order to provide a safer work environment for personnel. For animal rooms, the finished floor should slope 0.25 inches per foot toward the back of the room into a floor trench that flows to a flushing-rim floor drain. The drain should be covered by a grate that prevents large objects such as enrichment toys from entering the drain. The grate should be made of materials, such as fiberglass, which are resistant to chemical degradation and corrosion.

D. Finishes

A typical painted finish over CMU partitions should consist of two layers of block filler with a finish coat of industrial-grade epoxy paint or other specialized coatings to achieve a "pinhole free" finish. Several new paint systems exist which provide thicker coating than epoxy paint alone, and are more resistant to the effects of water and disinfectants. Plastic panel systems can be applied over CMU to increase resistance to water and chemicals, as well as alleviate the need for painting. These systems should be installed carefully and properly sealed to be sure that space between the wall surface and the veneer is minimized to prevent the harborage of vermin and the growth of bacteria. If these systems delaminate, they must be quickly repaired to prevent build-up of moisture and more extensive delamination. Circulation areas should receive corrosion-resistant metal wall protection guard rails placed at a height along the wall to coordinate with any rack projections, in an effort to maintain the required level of finish and reduce marring. Aluminum, stainless-steel or FRP corner guards should be placed on outside corners of walls to protect them from chipping.

A typical ceiling finish consists of a water-resistant gypsumboard suspension system located a minimum of 10 feet above the finished floor at the high point of the room, with a finish coat of epoxy paint or other specialized coating for a smooth, "pinhole free" finish. This waterproof system is critical, since daily husbandry practices often require that ceilings be washed.

IV. INDOOR HOUSING FACILITY CONTAINMENT CONSIDERATIONS

Indoor NHP holding facilities are typically constructed to meet at least the minimum requirements of ABSL-2 containment standards because of infectious agents typically harbored by NHP species. In most circumstances, ABSL2 containment in NHP facilities is enhanced by the use of ABSL3 performance standards by personnel. Although not an official containment classification by the *BMBL*, these facilities are often described as providing "ABSL2+" or "ABSL2 Enhanced" containment.

In addition to the minimum containment standards published in the *BMBL*, design features impacting containment should be determined by risk assessment and the nature of work being performed in the facility (NRC, 2003). Decisions regarding the incorporation of more stringent containment standards impact the cost and the daily operation of the facility. Design standards that increase containment above minimum requirements result in more restriction and difficulty in the movement of personnel and equipment. Increased containment design features also reduce the amount of space available in a specified footprint for animal housing because of the need for additional corridors and anterooms. When designing containment facilities, engineering standards should be the primary measure for providing containment, with performance standards and PPE used as secondary measures to increase protection of personnel.

The discussion of indoor facilities generally assumes that animals will be housed in secondary enclosures (i.e., cages) within the animal holding room. Many NHPs are housed in various types of cages as primary enclosures within rooms. There are many options currently utilized for housing NHPs in large group enclosures within indoor facilities. Design of the individual holding rooms, as discussed in this chapter, will allow the use of various caging types that offer complexity and socialization that is limited only by funding and the innovation of the design team.

A. Animal Holding Areas

Animal holding room sizes should be standardized within a facility to provide maximum flexibility and allow cage-change out of entire rooms during cage sanitation procedures. In this configuration, animals can be moved to another room, leaving the dirty room to be completely disinfected without animals in it. A NHP holding room measuring 13 feet by 21 feet allows housing of approximately 20–32 NHP of less than 10 kg body weight with enough free space to move caging racks within the room for thorough daily cleaning. If small groups of animals assigned to many different research projects are anticipated, the size of the animal rooms should be smaller in length to prevent wasting space. Large animal rooms within a fixed footprint are less costly to construct, but will not be optimally utilized if only portions of the room are filled with animals. The rectangular shape of the housing room allows caging to be placed along the longer sidewalls, which creates a central walkway between cages (Figures 21-2, 21-3). The room should be wide enough to allow personnel to move freely through the central walkway without being touched by animals housed in cages on either side. This dimension ranges from 5′6″ to 7′0″. This space provision also allows the placement of monitoring equipment, such as portable video cameras, to monitor animal activities. This practice is routinely used for monitoring the compatibility of socially housed animals during their introduction, as well as for research studies.

Ventilation should be provided in accordance with criteria from the *Guide* (ILAR, 1996). An independent ducted exhaust air-ventilation system should be used to create directional

Fig. 21-2 Interior of a NHP housing room.

Fixed equipment in a NHP housing room should include troughing for waste drainage from caging, wall-mounted chemical dispensers for daily cleaning, and water lines for automatic watering systems (seen at the top of the wall). Water lines and hose units should be located to prevent access by NHP. Troughing configurations differ based on type of caging used. In this photograph, an upper stainless-steel trough and lower floor trough is used. A trench drain is present at the opposite end from the room entrance.

Fig. 21-3 Interior of a NHP housing room with caging.

The same animal holding room as Figure 21-2, with rolling rack-mounted cages in place and attached to wall brackets for stability. There is enough room at both ends of the rows of cages for personnel to wash behind the caging with minimal effort. The width of the walkway between cages ensures that non-human primates cannot touch personnel walking in the center of the room.

airflow from areas of least contamination toward areas of the most contamination (CDC, 2007). Usually, this model suggests that air flows from gowning and shower areas toward animal holding and procedure rooms. In ABSL2 housing, the exhaust air is not required to be filtered, but should not be recirculated to any other area of the building. Directional airflow indicators should be present for each housing room, and should be visible from a distance to ensure that personnel are aware of possible problems with pressurization in the rooms should they occur.

The animal housing rooms should be designed to facilitate cleaning and housekeeping. The interior surfaces (walls, floors, and ceilings) should be water- and chemical-resistant. Electrical outlets in NHP housing rooms should be protected from moisture with spring-activated waterproof covers, and be GFCI-enabled because of the large amount of water used in these areas for cleaning. Drains positioned in NHP housing areas should be of the deep seal type to allow filling with chemical disinfectants or other solutions to minimize bacterial growth and vermin entry. Rim flushing drain units assist in moving large amounts of waste through the system. The type of sanitary system provided after the room drains is dependent on local ordinances, and can range from drainage directly to the municipal sewerage system to a requirement for a pretreatment plant at the research facility.

Built-in equipment is necessary for each NHP housing room to streamline husbandry practices, to provide access to water for animals, for cage security, and to provide ready access for frequently used items. Each holding room should have an automatic watering system with quick disconnects to accommodate the NHP caging system in use (Figure 21-3). The plumbing for the animal watering system should allow the ability to turn off the water supply to one side of the room at a time. This is particularly important when repairs to the water line are required due to unforeseen breakage either by personnel or NHP. The ability to turn water off on only one side of the room at a time will minimize the impact to other animals in the facility during the repair process. Wall-mounted animal watering systems are typically constructed of either stainless steel or PVC. Stainless steel is stronger and more durable than PVC, but is more expensive to install and maintain, particularly if accidental breaks occur. PVC, though subject to more frequent breaks, is fairly inexpensive to install, and easier and faster to repair. High and low drainage troughs, and brackets for locking down cage racks, if required, are mounted to the side walls of the animal holding room. If wall brackets are used for securing cages and cage racks then particular attention should be paid to anchoring these brackets, as large NHP are capable of shaking cages violently, which results in separation of brackets from the wall. A wall-mounted mop rack, hot and cold mixing station and detergent attachment for hose-down are necessary in each animal room. All hoses and chemical proportioning stations should be located well away from the front of animal caging, since NHP are prone to reach out for these items. A station located in the center of the wall at the rear of the room is optimum (Figures 21-3a, 21-3b). Thought should be given to placing wall-mounted brackets in each animal room that are capable of holding containers for sharps disposal. Having these containers readily available

encourages animal-care staff to dispose of sharps immediately after medications or anesthetics are administered.

B. Procedure Areas

All NHP housing facilities should include procedure rooms, which are used as medical clinics and to support research procedures. The number of procedure rooms required in each building is determined by considering the number of different species of NHP housed in the building and the types of activities that are necessary. If animals of different viral status will need to be accessed at the same time, then creating several small procedure rooms is required in order to keep these animals separated. If a large number of research support procedures are required on a daily basis, then more procedure rooms are necessary. Common anterooms or corridors should not be used as procedure areas because commingling of animals assigned to different research projects cannot be avoided and routine husbandry practices such as moving caging in and out of the building cannot be performed when research activities are taking place. Facilities used for the housing and treatment of animals originating from breeding colonies that have differing viral status require that more rooms be available to prevent cross-contamination.

Procedure rooms should be designed so that blood collection, physical examination and minor surgical procedures can be performed (Figure 21-4). Each room should have several folding, wall-mounted procedure tables which allow for space saving and convenience, at least one movable exam table for flexibility, and a standing-height lab bench with stainless-steel countertop and integral stainless-steel sink. Overhead medical examination lights mounted on a sliding track should be present over each folding and movable examination table. There should be ample storage space for medical supplies. Other closets and cabinets should be available in the procedure room to store PPE. Data connection or wireless connection as well as phone lines should be available in each procedure room to allow access to the animal database system. Procedure room sizes should be standardized, as with animal housing rooms, to provide maximum flexibility.

Fig. 21-4 Procedure room in indoor NHP facility.
Procedure rooms are used for performing examinations and minor procedures in NHP, and should be equipped with adequate numbers of examination tables, examination lights and storage spaces for supplies. In addition, data connections should be available to access the animal records database. Procedure rooms need to be in close proximity to animal housing rooms to minimize the necessity to transport NHP to other facilities.

C. Anterooms

Anterooms provide a transition zone between the ABSL-2 animal holding areas and non-animal areas. Anterooms provide additional security, which can be used to restrict movement of unauthorized personnel and to limit the movement of NHP in the event of an escape from an animal room. Additionally, anterooms serve as an area to garb in and out of PPE. Doors in anterooms should be interlocked. These rooms vary considerably, depending upon the available space and the number of personnel they will service. The size of the anteroom should accommodate the movement of caging racks and other large equipment in and out of the animal housing area, and also allow storage areas for PPE. Anterooms designed exclusively for personnel access only may be smaller, but consideration should be made to making the rooms large enough for storage of PPE and to allow several individuals to garb in PPE at the same time. Anterooms should be located at all entry/exit sites to the animal holding areas. Entrances to animal areas should be controlled so that personnel can only enter animal areas through anterooms. For areas where higher containment is required, such as quarantine, additional anterooms may be present within the facility or on each animal holding room. For anterooms used by personnel for entry, the space should contain adjustable wall shelving for the storage of PPE, a knee-operated hand-washing sink, a soap dispenser, a paper towel dispenser and a trash receptacle. Storage for footwear such as work boots that are left at the facility should also be provided. Flooring and wall finishes should be the same as in animal holding rooms and procedure rooms.

D. Personnel Use Areas

1. *Locker Rooms*

Since the use of work uniforms and PPE is required in NHP facilities, locker rooms should be large enough to accommodate the needs of all animal-care, veterinary, research and janitorial staff that work in NHP areas. Locker-room facilities can be centralized on the campus, or built in each NHP holding facility. Locker rooms built into each animal facility,

while more costly than centralized facilities, allow personnel who work in the building the ability to shower and change out of potentially contaminated work clothes prior to leaving the building. Shower facilities should be present in locker rooms, as showering prior to changing into regular clothing is a required protocol for many facilities. Separate locker rooms should be provided for men and women. A typical aggregate locker-room size for a facility housing 300–500 NHP is approximately 30' × 36'.

2. *Office Space*

Because of the need to maintain containment at ABSL2 levels in NHP facilities, it is prudent to provide office space within the containment area to facilitate daily administrative and record-keeping requirements. If the office space is maintained at positive pressure with respect to the corridor and animal holding rooms, standard operating procedures may allow removal of PPE when in the office area. The office may have windows to provide natural light, which can be psychologically important for staff who might be working in the facility over the course of 8 hours.

3. *Storage*

As in other types of laboratory animal facilities, the design of NHP facilities should include ample amounts of storage space to meet the needs of daily husbandry, medical care and research activities. Specific storage areas to consider in NHP housing facilities include rooms for medical and research equipment and supplies, janitor's closets for storage of cleaning chemicals and other cleaning supplies, food storage, and room for storage of husbandry and related equipment. Additionally, clean cage storage should be considered, but is most likely to be on the clean side of the cage-wash area. The provision of adequate storage space minimizes the tendency to store equipment and materials in corridors and rooms designed for other purposes.

The use of PPE is required in NHP facilities, and the amount of storage space necessary can be tremendous. Storage areas should be able to accommodate a minimum of a week's supply of PPE, husbandry and medical supplies. Constructing a central supply building separate from animal housing and procedure buildings can enhance storage capabilities, but does not eliminate the requirement for storage in the individual animal facilities.

4. *Circulation Corridors*

The function of the circulation corridors is to allow movement of personnel, supplies and equipment through the facility. During the design phase, the course for travel of dirty and clean caging racks should be considered to minimize the risk of cross-contamination.

Corridor designs for facilities housing NHP are similar to single- and multiple-corridor designs seen in facilities housing a number of different species. The cost-to-benefit ratio of multiple-corridor design should be determined during the design phase of the project, and will be based on available space, containment level, available animal-care personnel, level of funding, and type of research programs housed in the facility. The number of corridors in any footprint increases as the level of biocontainment is increased.

There are special considerations for corridors in facilities housing NHP that should be taken into account regardless of the number of corridors designed into the facility. Sinks should be placed in corridors to allow for use in the case of an accidental exposure to NHP, and also for routine hand-washing (NRC, 2003). Hand-washing should not be attempted inside a NHP housing room because of the potential for contamination. All built-in equipment in corridors, including signage, sinks, emergency showers, fire alarms, door hardware, etc., should be adequately protected from collision with cage racks and other large equipment when it is moved through the corridors (Figure 21-5). Larger pieces of equipment, such as sinks, may be recessed to protect them from collisions with rolling cage racks. This is especially critical for animal housing room corridors, where cage-washing activities can require movement of large numbers of cages on a daily basis.

Corridors to animal housing rooms should be wide enough to accommodate large equipment that must be moved through them for routine animal-care procedures. Large rolling racks

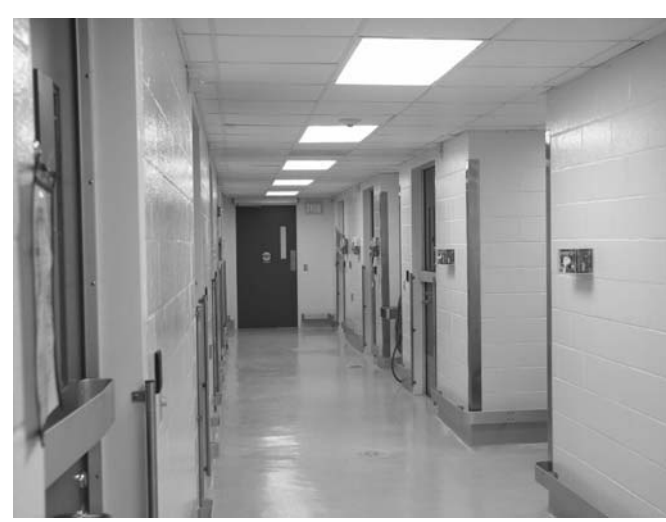

Fig. 21-5 Animal housing room corridor.
Corridors should be wide enough to facilitate movement of large caging racks and other equipment. All signage and wall-mounted equipment should be adequately protected from collisions with equipment moving through the corridors. Hand-washing sinks should be present in the hallway in case of an exposure to NHP. Note that the sink is recessed from the main corridor and signs are mounted on the wall rather than hung from the ceiling to prevent damage. Floor drains should be present in the corridor to allow hose-down during cleaning.

of cages must be easily negotiated in and out of the animal room, and be able to make the turn in the corridor with extra space to minimize the possibility of equipment collisions with walls. The minimum width of all corridors is preferentially 7'-8', to accommodate caging racks and allow for bumpers.

V. OUTDOOR HOUSING FACILITIES

Outdoor housing facilities for NHP are principally used to allow the housing of social groups for breeding. Additionally, this housing type has been used to maintain groups of animals assigned to behavioral and other research studies where the requirement for accessing individual animals is minimal. Outdoor group housing facilities are less costly to construct than indoor facilities.

Local environmental and climactic conditions are primary determinants of whether outdoor housing should be constructed. Construction of outdoor enclosures requires thoughtful discussion regarding security for both animal containment and exclusion of unauthorized personnel. These issues become more important when the facilities are to be located in or near populated areas. The impact of noise and odors for neighbors of the facility may preclude the construction of outdoor sites. In most cases it is advisable, especially if several enclosures are being contemplated, that a buffer zone be present around the structures to allow for security, as well as visual and sound-reducing barriers. Local ordinances may restrict the construction of certain types of holding facilities, and should be consulted early in the planning process. In many areas, environmental impact studies must be completed prior to construction. The results of these studies may eliminate the possibility of locating animals in outdoor housing.

Different species of NHP have variable tolerances to extremes of temperature, and local climatic conditions will dictate the feasibility of housing animals in this manner. Rhesus monkeys (*Macaca mulatta*) have a large geographic range in the wild, and can accommodate a large variation in environmental temperature. These animals can be raised outdoors for the entire year in the southernmost United States. African species such as sooty mangabeys (*Cercocebus torquatus atys*), African green monkeys (*Chlorocebus aethiops*) and baboons (*Papio* species), as well as other macaque species such as pigtail macaques (*Macaca nemestrina*) and cynomologous macaques (*Macaca fascicularis*), may require additional shelter and in some cases supplemental heat during winter even in the southernmost states on some days.

There is a wide variety of materials and designs that are being successfully utilized for production of NHPs, including islands (enclosures surrounded by water); electric fencing; galvanized chain link; stainless-steel fencing; brick walls covered with concrete; and various flooring substrates, including galvanized or stainless-steel raised wire grid, sand, river rock, concrete (sealed with various products), ceramic tiles and other materials. These various materials are chosen primarily because of cost, availability and design requirements. It is beyond the scope of this chapter to address or describe all of the possible types of facilities or materials that can be utilized in the construction of outdoor housing for non-human primates. While providing alternatives in the text, the authors have focused the information as related to their specific experiences and success in design and construction of NHP facilities.

A. Types

Many different types of housing facilities have been utilized for housing NHP outdoors. The most commonly used configurations for outdoor social housing include corncribs, runs and field cages/corrals. The choice of the type of outdoor housing should be based on the species, number of animals, local climactic conditions and local topography. Corncribs and runs are designed to house small numbers of animals, while field cages/corrals are usually designed to house larger numbers of animals. Several types of outdoor social housing enclosures can be constructed of prefabricated components that are assembled on site, which decreases construction time but may increase cost and limit the ability to make modifications.

With the recent emphasis on providing well-characterized, virus-free NHP for research, most institutions are choosing to house smaller groups of animals to minimize the number of animals impacted if viral infection or other disease outbreaks occur within a specific enclosure. Runs and field cages/corrals can be constructed with attached indoor areas, allowing animals the ability to move into more controlled, sheltered environments. The AWA and the *Guide* provide information regarding requirements for outdoor facilities. Examples of corncrib, run and field cages/corral enclosures can be seen in Figures 21-6–21-10.

Fig. 21-6 Corncrib housing.
Corncribs are used to house small groups of NHP. Several units can be connected together by a common safety/procedure area to maximize the use of space and increase security. All access points to the corncribs are contained within the safety/procedure area to increase security.

Fig. 21-7 Indoor/outdoor runs outdoor area.
Runs are usually configured to have both indoor and outdoor components. Runs can be built to any size, but are commonly built to house small groups of NHP, similar to corncribs. Note that all of the outdoor enclosure components are surrounded by a safety area constructed of chain link.

Fig. 21-8 Indoor view of indoor/outdoor runs.
Indoor areas of runs should be able to accommodate all animals housed in the run at one time. Indoor areas typically have heat and ventilation. The indoor area in the photo is air-conditioned. Epoxy floor covering is present throughout the indoor and outdoor sections.

Fig. 21-9 Field cage, exterior view.
This field cage, including the roof, is constructed of galvanized chain-link fabric and is completely enclosed. The roof of the enclosure expands the amount of usable room by providing opportunities for brachiation.

Fig. 21-10 Corral, interior view.
Corrals do not have roofs, and provide containment of animals by using sheet metal or another smooth surface for the wall structure. The corral in the photo uses a combination of chain-link fabric on the lower section and sheet metal, which is set at an angle to increase security. The lower section of chain-link fabric allows air movement and provides adequate space for observation of animals from the exterior of the corral.

The size of the structures can vary, and is based on the number of animals that are to be housed in them. The number of animals to be housed in a specified space is variable, but should meet the minimum space requirements and guidelines of the AWA and the *Guide* for the particular species housed. Space requirements in group housing enclosures may be better defined by behavioral standards rather than by body size (NRC, 1998). In most cases, animals in outdoor housing facilities have more than the minimum amount of required space available because the social structure and related complexities

of dominance hierarchies can limit the number of animals that can be housed in a specific area. It is important to use both industry standards as well as continued evaluation of behavior and health to provide guidance as to proper population density in group housing facilities.

B. Security

Security of outdoor enclosures should be of particular concern when designing these structures, as escape from these facilities is more likely to have a greater impact than an escape from a primary cage enclosure located in an indoor facility. The escape of NHP into communities poses concerns with respect to public safety and public relations, even if animals are used as breeding stock with no experimental manipulation. NHP are intelligent, and may be capable of defeating security systems that are adequate for other species. Security practices and construction design criteria should be regularly reassessed and tested. Consultation with professional security management and design companies should be included in the budget for construction of outdoor housing facilities.

Security should be approached as a comprehensive plan which includes security personnel, training for animal-care personnel, security design features of the primary housing structure, and security design features of the areas surrounding the primary enclosures. When planning the site, a buffer zone should be present around the primary enclosures in order to limit the transmission of odors and noise, and eliminate or reduce the visualization of animals by neighbors. A minimum of 250 feet of wooded space outside of the perimeter fence has been proposed as typical. Additional space, if available, would be preferable. As required by the AWA, a perimeter fence should be constructed to enclose all of the primary enclosures and prevent the entry of wild animals. This security provision can be enhanced by adding an additional inner perimeter fence. The minimum design standards for construction of perimeter fences, as outlined in the AWA, provide for limiting the access of unauthorized personnel and large mammals, but only provide minimal protection for containing NHP in the event of an escape from the primary enclosure. More robust fencing should be considered, which will contain NHP if the primary enclosure security is breached. This fencing should have a solid component, such as sheet metal, secured in such a way as to minimize hand- and finger-holds for NHP. Fencing components as small as rivet ends can be utilized by NHP and allow them to climb over a wall. The fence should be a minimum of 20 feet tall to prevent most monkey species from scaling it. For added security, the top section of fence can be angled toward the enclosed area at approximately 15–20 degrees (Figure 21-11), as has been used in corral construction (Alexander *et al.*, 1969). Construction of a roadway between the fences adds additional security by allowing patrols along the road (Figure 21-12). Camera and motion-detection equipment along all perimeter areas allows the detection of unauthorized personnel as well as escaped animals.

Fig. 21-11 Unscalable perimeter fence.
The AWA provides standards to be used for preventing access by large mammals and unauthorized personnel. Consideration should be given to providing perimeter fences that prevent escape of NHP in the event that the primary enclosure is breached. The same design as used to prevent climbing of walls in open-top corrals can be considered for this purpose. The photograph shows one type of unscalable fence that might be used around the facility perimeter.

Fig. 21-12 Perimeter security road.
Adding a perimeter road that follows the inside of the exterior perimeter fence can enhance security around outdoor housing facilities. The road allows vehicular patrols decreasing response time in the event of a security breach. As an additional security measure, an inner perimeter fence may be constructed, as in Figure 21-11. Video surveillance equipment with 24-hour monitoring should be put in place around the perimeter.

The number of gates to primary enclosures should be minimized. Additional entry gates are convenient, but provide more opportunities for security failure. At each gate entry site, several

Fig. 21-13 Field cage entry gate, safety area and locking mechanisms.
All entry sites to outdoor housing areas should have a two-gate entrance with a safety area. Each gate should have multiple locks to increase security at these locations. The photograph shows a personnel entry gate into a field cage. The gate has a large bolt-locking apparatus that must be unlocked and held at a 90-degree angle to the doorframe to be opened. In addition, two other locks are present on the door. The safety area has a roof to contain animals in the event that they breach the inner door and enter the safety area.

Fig. 21-14 Procedure area in field cage.
Each outdoor housing area should have an area to perform examinations and minor procedures. This area can double as the safety area for entrance to the housing enclosure. The area should be large enough for equipment and necessary personnel to perform required activities. As in the photograph, the capture chute system is usually contained in the area. The procedure area in the photograph measures 10 feet in width and runs the entire length of the field cage (100 feet).

redundant locking mechanisms should be present (Figure 21-13). All walls of the enclosure should be embedded a minimum of 6 inches in a concrete footing to keep NHP from escaping under the fence. The concrete footing may incorporate drainboards for the watering devices, and be wide enough to prevent the growth of foliage next to the exterior walls of the enclosure. This provision also prevents wild animals from entering.

C. Facility Components

1. *Procedure Areas*

As with indoor NHP housing areas, outdoor housing should have procedure areas where veterinary care, collection of biologic samples, and minimally invasive research procedures can be performed (Figure 21-14). Most research studies involving animals housed outdoors are limited to behavioral observation or minimally invasive collection of samples. As such, the construction guidelines for outdoor procedure areas are not as critical as for indoor facilities. In outdoor facilities that have an indoor component, such as indoor/outdoor runs, procedure areas may be located indoors. Multiple corncribs can share the same procedure area, which may double as a safety enclosure (Figure 21-15).

The procedure area for a field cage or corral should be large enough to allow adequate room for the movement of equipment and personnel. The capture chute system (see below) will occupy a portion of the procedure space, and allows for

Fig. 21-15 Safety/procedure area in corncribs.
Safety areas for corncribs have the same design requirements and components as in field cages. The example in the above photograph demonstrates how several different corncrib enclosures can be linked using one safety area. Since these structures are built on concrete, drains should be placed to facilitate drainage.

access to animals. In divided field cages, a central procedure space should be accessible to all divided portions of the cage. Equipment such as tables, scales and examination lights should be moved out of the open procedure areas after use to prevent degradation of the equipment in extreme environmental conditions. The procedure area should be designed to allow entrance of personnel through a safety/security gate without having to

enter animal areas. A light roof structure may be constructed over the procedure area in order to keep personnel working there out of the weather. This may also be accomplished by applying removable covers, such as tarps, when animals need to be accessed. In some cases, removable shade structures for personnel, such as tarps, are preferable, as vermin tend to congregate in permanent roof structures in outdoor facilities.

2. *Safety Enclosures*

Safety areas should be designed in outdoor enclosures to provide security by increasing the number of doors between animals and the exterior of the housing structure (Figures 21-13, 21-15). Safety areas should be present on all outdoor structures discussed in this section, which includes corncribs, runs, and field cages/corrals. Safety areas are analogous to anterooms in indoor animal housing areas, and have an external door, a working space, and an inner door which leads to the animal holding area. There should be a safety area associated with every door to the animal enclosure. It is preferable to have separate safety areas for moving large equipment and for personnel. Large doors are necessary for moving equipment in, such as mowers and land-moving equipment, which are required for maintenance, but are not used on a daily basis. Smaller doors used for personnel movement are usually stronger, by nature of their size, and offer less of an escape hazard. The safety area should be covered with a secure roof, which can be constructed of the same material as the animal holding area (chain link, wire bar).

3. *Chute Systems*

At times it is required that NHP who are housed in groups be accessed for evaluation, medical treatment or other reasons. In small enclosures such as runs and corncribs it is feasible to capture most species of research NHP using netting equipment, but when possible it is preferable to train NHP to enter a chute system in these situations (NRC, 1998). For larger group housing structures, such as field cages/corrals, it is imperative to have chute systems in place for animal capture because of safety concerns for personnel and animals.

Chute systems can be constructed from the same materials as the primary enclosure (chain link, wire bars), and should be secure with coverage on all four sides. For divided corrals, separate chute systems should be constructed for each divided area to help minimize contamination between different groups of animals (Figure 21-16). If the chute system is built as a permanent fixture in the holding facility, the floor of the structure can be used as the floor of the chute. This flooring should be finished concrete to prevent animals from having to run over wire bars or chain link. In cases where square footage in the enclosure is in short supply, movable chute systems can be designed which allow attachment to doors on the primary enclosure (Figure 21-17). These chutes should have a floor structure built in. Large, weather-resistant casters should be present on the chute to assist personnel in moving it from one location to another.

Chute systems should be designed to incorporate sliding doors to separate animals. The sliding doors should each be secured externally by padlocks and chains or other methods,

Fig. 21-16 Capture chute system in field cage.
The capture chute system is located in the safety/procedure area, and is fabricated from the same materials as the primary housing area of the field cage. The chute system in the photograph has a top that can be opened to facilitate access to animals. The separating panels (present at the end of the chute in the photograph) are made from sheet aluminum. The chute system also has integrated squeeze backs to allow the administration of medication or anesthetics without having to remove the animal from the chute. All sliding panels and doors must be secured with locks.

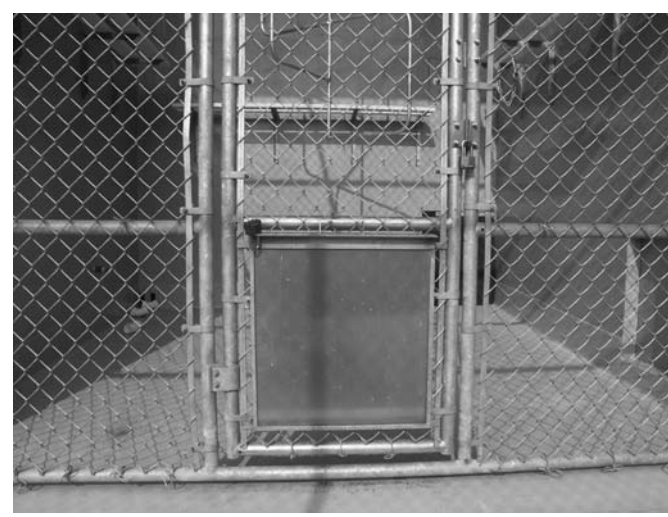

Fig. 21-17 External door to run with chute port.
In enclosures without built-in capture chutes, a port should be constructed so that portable chute systems can be used. In the photograph, a chute port has been created in the access door of a run. The port should have a locking door that cannot be accessed by NHP held in the enclosure.

and should be made of materials resistant to decay and warping. Sheet aluminum is a good choice, as it has the additional benefit of being lightweight. Divider panels can be placed at intervals that allow several NHP to occupy the same space. Squeeze backs should be incorporated in the design to allow the administration of therapeutic agents or anesthetics without the need to hand-catch the animal. Lockable, hinged openings above each section of chute enable personnel to access anesthetized NHP easily. Padlocks should secure these hinged doors. In addition to the hinged doors on top of the chute, a hinged or sliding door should be present at the end of the chute system to allow unanesthetized animals to run into transfer cages, secured to the doorway, for transport.

4. *Primary Housing Area*

Although the size of the housing area in outdoor enclosures can vary, most institutions are decreasing the sizes of social groups of NHP in order to better control breeding and reduce the number of animals involved in disease outbreaks. The primary housing area should provide enough space for each individual NHP as specified in the *Guide* and the AWA. Adequate shelter should be constructed so that each individual can obtain shelter at the same time.

The flooring of the primary housing area can be concrete, stone or earth. Additionally, runs and corncribs can be built above grade with grid flooring and a concrete subsurface which makes daily cleaning easier. Stone and earthen floors require regular maintenance to keep them free of excessive waste, and should be raked and cleaned frequently enough to prevent the accumulation of organic debris (AWA, 1991). In environments where rainfall and sunshine are abundant, biologic and natural degradation of wastes can be very efficient on natural surfaces and will assist in the control of build-up of waste products. Naturalistic flooring, such as stone and earthen floors, has the benefit of allowing more complexity and provides the potential for plant growth and foraging opportunities as part of the environmental enrichment program (Figure 21-18). In order to assist in maintaining the growth of vegetation and decrease organic debris and pathogen loads, animals may be removed from enclosures on a regular basis to allow the surface to "rest." This is accomplished by constructing more enclosures than are necessary and leaving them vacant for rotation purposes. The type of stone to be used on floors should be chosen to provide a comfortable walking surface for NHP and minimize the potential for injury. Stones with sharp edges should be avoided. A drainage bed can be constructed by adding a layer of sand below the layer of stone. Some NHP will ingest stones or place them in cheek pouches, which may cause health problems. Concrete floors can be finished with epoxy or other similar material to enhance their durability. Concrete floors should incorporate a drainage system. Depending on the outdoor location, these drains may be subjected to accumulation of natural debris such as soil and leaves. Because concrete may become excessively cold during winter months, provisions such as warm-water recirculating systems or adding hay and other bedding substances should be considered in colder climates.

Climbing structures, shelters, toys and perches should be present in the primary housing area. Design of these structures should eliminate the possibility that animals might use them to escape the enclosure. Many novel climbing structures, such as ferris wheels, are available commercially (Figure 21-19).

Fig. 21-18 Naturalistic flooring with vegetation.
Natural earth floors in field cages, corrals and runs can support the growth of vegetation, which provides complexity and foraging opportunities for NHP. In the photograph, pigtailed macaques forage for birdseed and cracked corn in a field cage with a soil floor.

Fig. 21-19 Prefabricated field cage and corral furniture.
Several types of field cage and corral furniture can be purchased directly from manufacturers for installation. The photograph above shows a ferris wheel and calf shelters that have been used to provide enrichment and shelter.

Other climbing structures can be constructed from common building materials such as PVC pipe, aluminum, steel, wood and other plastics. There should be enough perches available in group housing structures to allow all animals to have access to a perch at one time. For field cages with tops, the posts used to support the roof can be used to provide the structure to span perching material or other climbing enrichment. Perches should preferentially be constructed of materials that do not conduct heat or cold, such as high-density plastic, wood, or simulated wood products (Figure 21-20). Perches constructed of wood should be replaced when excessively soiled or worn (AWA, 1991; ILAR, 1996). Tubular or angular metal frames should support the outer perching material in order to give the structure more strength. The seating surface of the perch should be wide enough to accommodate the largest animals. Typically, 6 inches or more is required as a seating-surface width.

5. *Watering Systems*

Potable water should be supplied to each outdoor housing facility using an on-demand watering system. Large, sturdy valve devices, such as those used for swine, are preferred for outdoor use. Water outlets should be provided at multiple sites to allow an adequate supply of water for subordinate animals (NRC, 1998). A small concrete slab to direct runoff from the water sources should be put in place to minimize the amount of pooling water where naturalistic flooring substrates are used. This structure may be incorporated in the concrete footing (Figure 21-21). All above-ground components of water lines should be protected from extremely cold temperatures, and should be marked so that they are visible to grounds crew and other facilities personnel from a distance to avoid accidental breakage by equipment. When many enclosures are in the same location, water shut-off valves should be placed so that, when required for maintenance, one section at a time can be shut off, causing less impact to other animals in the area.

Water sprinklers may be added to outdoor enclosures to aid in cooling NHP during the warmer months of the year. Other benefits of adding sprinkler systems include adding complexity to the animals' environment for enrichment purposes, and providing irrigation for growth of plant material and runoff for sanitation purposes. Sprinklers should be mounted in such a way so that direct spraying of water on animals does not occur, and so that an animal may seek shelter from the water if it chooses. Mounting sprinklers on the roof structures of field cages is one way that this can be accomplished.

D. Construction

1. *Corncribs*

Corncribs are usually constructed from prefabricated components that include large-gauge wire or rods welded and bolted together to create a cylindrical enclosure (Figure 21-6). A prefabricated domed or flat roof is bolted to the cylindrical structure. Many of these roofs have breakaway portions at the apex that help to decrease the chances of them flying

Fig. 21-20 Perching in run.
Material used for the seating surface of perches should not conduct cold or heat, in order to prevent overheating in the summer and drawing body heat from animals in the winter. Materials that fit this qualification include wood, plastic and simulated wood products. The photograph shows a high-density plastic seating surface with a stainless-steel support structure mounted on the wall of an indoor/outdoor run. The support structure is critical, since leaping and climbing on the perches places a tremendous amount of force on them.

Fig. 21-21 Watering device in field cage.
This photograph shows a swine type on-demand watering device used for non-human primates in a field cage. These devices should be approximately 18–24 inches from the ground to allow animals to drink while sitting. The area around the watering device should be graded to assist in diverting water outside the enclosure and decrease pooling. The concrete diverter seen in this figure is incorporated in the concrete footing.

long distances in the event of strong winds. The corncrib is usually fixed to the surface by bolting it into a concrete slab. The concrete slab can be used as the flooring, or the corncrib can be raised on legs with a grid bottom to allow waste to fall through to the concrete slab below. The concrete slab should be finished with troweled-on epoxy or sealed if in direct contact with animals. Round river rock has also been successfully used as a floor substrate in corncribs, but must be changed as necessary. Corncribs can also be anchored into the ground and supported on cement blocks or other material, with a round drainage rock substrate. Corncribs may be attached to buildings or other enclosures to provide an indoor/outdoor facility. In addition to the corncrib structure, gates and safety/procedure areas are constructed of the same heavy-gauge metal or chain-link fabric. These safety/procedure areas should be large enough to accommodate personnel and capture systems such as portable or fixed chutes. The safety/procedure area should have a roof (Figure 21-15) made of chain link or sheet metal. Multiple corncribs can be linked together in pods using these security areas centrally. If concrete flooring is used, drains may be placed in each individual corncrib and in the security area for hose-down during daily cleaning.

1. *Runs*

Similar to corncribs in size, runs typically house small groups of animals and many times are constructed as indoor/outdoor facilities. The benefit of attaching outdoor runs to indoor facilities is that this may allow outdoor access for NHP in areas where temperatures range outside of those generally accepted as normal for specific species of NHP. The attached indoor facilities may be designed with heating, ventilation and air conditioning, but most commonly are provided with heat and exhaust only. The indoor component of the run must be able to accommodate all the animals housed in the run at one time. Water must be made available in both the indoor and outdoor areas in the event that animals must be locked in the indoor section during inclement weather. The flooring of the run is most commonly concrete with a troweled-on finish such as epoxy, but naturalistic flooring is also acceptable. The side walls of the runs are usually constructed of CMU block and finished similarly to indoor animal housing areas. The front and back walls are constructed of chain-link fabric or bars to allow visualization. As an option, the outdoor run can be covered with a roof structure to provide additional protection. Care must be taken to ensure that animals from adjoining runs cannot make contact with each other. Secure locking guillotine doors with remote controls should be used to separate the indoor and outdoor components. These controls should be inaccessible to the animals housed in the run. Both mechanical and hydraulic systems have been used to control the guillotine door systems. As with other outdoor enclosures, the outdoor portions of the runs should be enclosed within a safety area for security. Access points on the indoor, outdoor or both areas should be constructed for attachment of portable chutes or use of built-in chutes for capturing animals (Figure 21-17).

2. *Field cages/corrals*

The terms *field cage* and *corral* have been used to describe large outdoor enclosures. Field cages are structures that have a roof, while corrals have open tops with unscalable walls to provide containment. For most new construction, institutions are choosing to build field cages because the roofs offer more security for the animals and provide other benefits such as increasing the area for brachiation and a surface for mounting shade panels and enrichment devices. Since both of these structures have many similar design aspects, this section will refer to field cages and corrals together except where there are notable differences.

The site for field-cage/corral placement should be graded to drain to the perimeter of the enclosure. This is usually accomplished by bringing in-fill material to raise the level of the center of the enclosure, which is allowed to compact prior to construction. Field cages/corrals are usually constructed of nine-gauge chain-link fabric that is supported by galvanized steel posts. Chain-link fabric and posts should be hot-dip galvanized to prevent deterioration and rust. Some investigators have noted zinc toxicity in animals housed in galvanized cages (Obeck, 1978; Stevens *et al*., 1978), but the exposure of animals to galvanized surfaces in large field cages and corrals is minimal. These materials can be substituted with other materials, such as bars made of aluminum or stainless steel, which add considerable cost to the construction. As stated above,

Fig. 21-22 Shade panel over perch in field cage.
The roofs in field cages can be used to support lightweight shade panels. In the photograph, sheet metal has been secured to the chain-link roof using ties at multiple sites. Shade panels must be secured in multiple sites to prevent damage by wind. Each perch in the enclosure should be covered with a shade panel. The support pipes for the roof structure have been used to span perching material across.

field cages have a chain-link roof structure, which is supported by posts on 10- to 12-foot centers. Increasing the diameter of centers that the posts sit on reduces the number of posts necessary, and allows large equipment to access the enclosure for grass cutting, earth moving, etc. All supporting posts used in the construction of field cages/corrals should be placed in concrete, and a concrete footer should be poured around the entire perimeter of the field cage/corral at a depth of 12 inches to secure the perimeter posts as well as the chain-link fabric so that animals cannot bend the chain link or dig out to escape. The supporting posts can be used to mount perches or other enrichment furniture such as swings, ferris wheels and barrels. The roof also can be used to support shade structures that can be mounted on the outside of the enclosure. Shade structures should be placed over perching to encourage animals to use perches (Figure 21-22).

As NHP breeding colonies become more characterized with respect to genetics and infectious agents, breeding groups have become smaller. Small breeding groups limit the possibility of transmission of infectious agents to large populations if one animal is infected, allow for ease in genetic management of the colony, and make complex social hierarchy issues easier to address. Large corrals ranging in size from less than 1 acre to several acres have been renovated into divided field cages by adding roofs and separating them into quadrants. Figure 21-23 shows the layout of a typical divided field cage. The specific parts of the field cage/corral have been described in an earlier section.

The four separate quadrants should have dividing gates between each of them, which allows them to be maintained as separate units or combined in different configurations when larger breeding groups are housed. The ability to combine

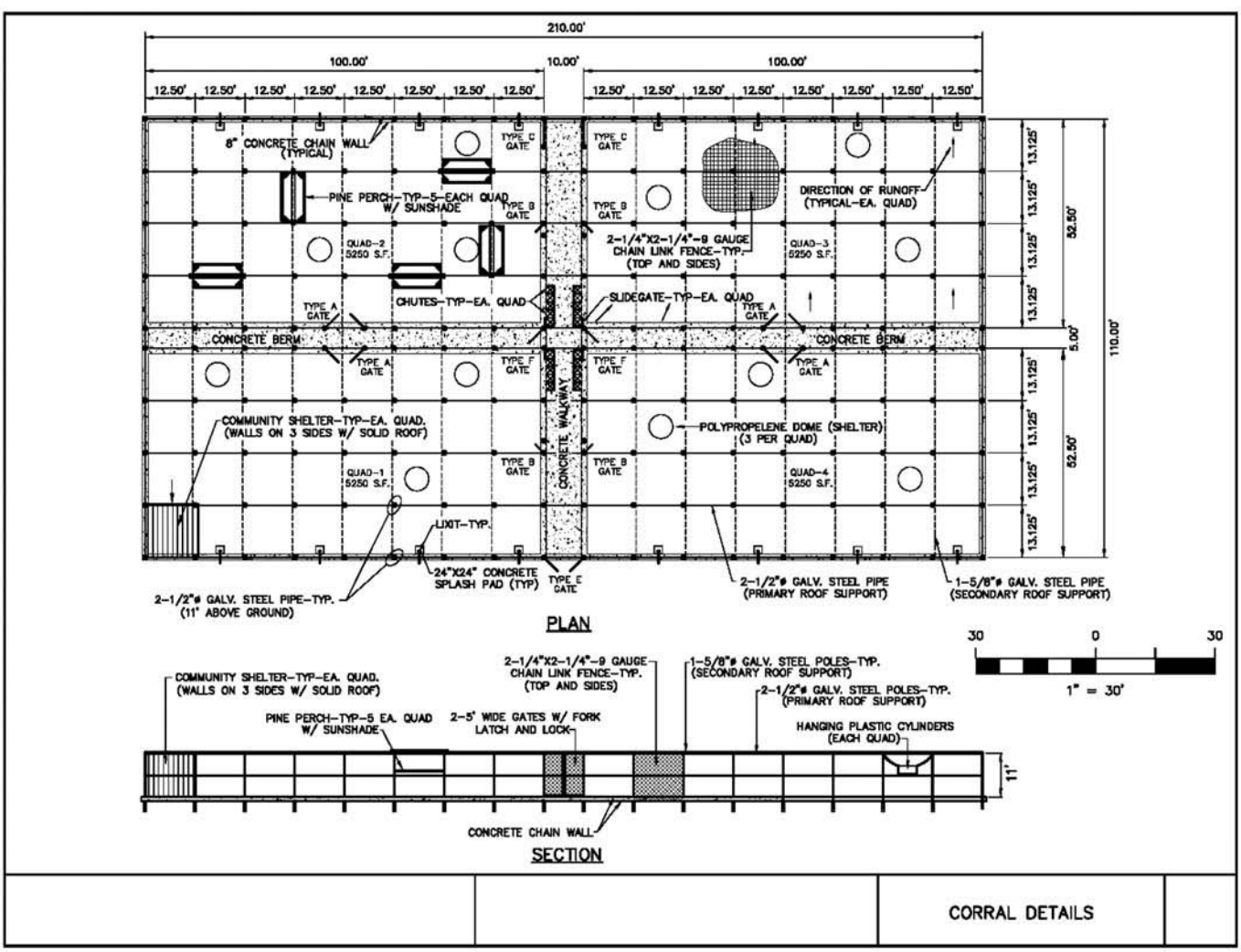

Fig. 21-23 Line drawing of field cage.

The line drawing shows design features for a typical four-quadrant corral with common procedure area and separate capture chute systems. Each quadrant is separated from others using the central corridor and berms. The quadrants can be combined by opening separating gates, which allows increased housing space and versatility of the enclosure.

Fig. 21-24 Berm for separation of enclosures in divided field cages. Berms are used to separate enclosures that are in close proximity by directing wastewater runoff away from adjoining enclosures and preventing contact between animals. The photograph shows a concrete berm that is within a divided field cage and is 5 feet wide.

Fig. 21-25 Permanent shelter in field cage.
The photograph shows a permanent shelter in a field cage that can be used in temperate climates. The walls and roof of the field cage are used as structures to attach panels to complete the structure. Ample perching should be available in the shelter to accommodate all animals in the enclosure. Adding movable shelter items as in Figure 21-26 can provide additional shelter. During colder months, additional panels and hay can be added to increase warmth. Heating elements can be added for further temperature control. Note in this example that a large door is present that can be closed during colder months to act as a windbreak. Translucent roof panels allow light to enter the shelter, which is especially important during winter when the shelter door is closed.

several units together enhances the structure's versatility and functionality. The gate system also allows movement of animals from one quadrant to another when necessary for maintenance and pasture rotation. All quadrants should be separated by enough space on all sides to prevent contact between animals. The path of drainage should be such that drainage from one quadrant does not flow across others. This can be accomplished by providing earthen or, preferably, concrete berms that are elevated at the center to force drainage water into the respective corral perimeter and away from other quadrants (Figure 21-24).

The central corridor of each field cage/corral should be wide enough to accommodate large equipment as well as a chute system for each quadrant. Since many of the animal-related procedures are performed in the central corridor, the space should also have electrical outlets and space for tables and other portable examination equipment. The chute systems are used to access animals during inventory procedures, for capturing animals for treatment and assignment to research projects, and for sample collection.

E. Shelter

Shelter should be provided for all types of outdoor enclosures, to permit all NHP housed in the area to escape from inclement weather or aggressors. Shelters can be built as part of the primary housing structure or added as movable components. In more temperate climates, shelters may only have to protect from rainfall and direct sun. In colder climates, more elaborate shelter is necessary and is usually provided by permanent outbuildings and indoor/outdoor facilities. An example of a built-in shelter for an area that experiences temperate climactic conditions is shown in Figure 21-25. Roofs on the shelters should incorporate translucent panels to increase light, which is especially important during winter. Permanent shelters, such as the one pictured, should have ample amount of substrate on the floor to increase drainage and facilitate cleaning, since animals will spend considerable amounts of time within the shelter. Shelters can be designed to have removable panels that allow more air movement during the warmer months, with windbreaks in the winter provided by the placement of additional panels. Figure 21-25 shows a door that can be closed during the colder months of the year. In colder climates, or when less cold-resistant species are housed, permanent shelters should be outfitted with radiant heating devices. These devices can be electric or gas-powered and need only raise the ambient temperature a few degrees, since animals will huddle together, providing some body heat. Heaters should be designed to minimize access by vermin, which could be drawn to the area because of the available heat. In addition, the heaters and electrical supply should be well out of reach of the NHP, and provide small enough openings so that infants will not be able to gain access to the heating elements. Radiant heat can also be installed in the floor through the use of hot-water piping or electricity. Although comparatively expensive, radiant heat in the floors promotes drying of the floor as well as assisting in body temperature maintenance.

Fig. 21-26 Movable shelter in field cage.
Movable-shelter items such as those used in the photograph above include calf hutches and barrel swings. Movable-shelter items facilitate husbandry practices. These shelters should be designed or modified to allow separate entry and exit points to allow a route of escape from aggressive cage-mates.

Thought should be given to creating novel shelter devices as part of the environmental enrichment program. These shelters can be created from many commonly used items, and can be relatively inexpensive. Figure 21-26 shows the use of plastic barrels suspended on stainless-steel cable to provide a shelter device that can be used as a swing. Since many of these shelters are destroyed by NHP during typical use, it is important to determine what health issues (if any) might result from their use, prior to instituting widespread implementation. Designs using PVC pipe and other materials are limited only by the imagination of the creators.

In order to allow even subordinate animals to find shelter, it is preferable to offer many different smaller shelters instead of a single or a few large shelters (AWA, 1991; ILAR, 1996). Shelters should be designed to be easily cleaned and allow for observation into them for daily health checks. The ability to move and relocate shelters easily assists with sanitation efforts. For warmer climates, shelters should have openings on both sides to assist in observation and allow an exit to a subordinate animal should an aggressor enter the shelter. Perching should be provided in outdoor housing areas, and a shade panel should be placed on top of each perch to encourage animals to use the perch during direct sunlight hours and when rain occurs (Figure 21-22). Shade panels should be made of materials that withstand the weather, such as corrugated sheet metal, and will not be destroyed by NHP using the enclosure. Figure 21-26 shows calf hutches being used as movable shelter devices. The mobility of these items enhances maintenance by facilitating sanitation, reducing fecal build-up and decreasing harborage of vermin. When possible, perches should be placed in the shelters to prevent animal contact with waste when occupying the shelter.

F. Drainage

When designing the layout for multiple field cages/corrals, consideration should be given to runoff of storm water since drains and underground sewerage are not typically used in these locations due to the use of naturalistic flooring materials, which would result in sedimentation of the lines. The use of subsurface drainage using fenestrated PVC pipe has been utilized in these environments at some institutions as an alternative, and may be most effective for rock floors as they allow drainage to the subsurface. Runs and corncribs with concrete floors usually have drains placed with wastewater directed and treated the same way as with indoor housing locations. Local laws and ordinances dictate how runoff should be directed and treated, and should be consulted prior to constructing these types of outdoor facilities.

Planned layouts for outdoor housing areas should allow for enough room for ditches, detention ponds, levees and other components of the drainage program. These structures should be located in such a way as to prevent drainage from moving from one housing structure to another. The necessary drainage components should be located in a way that allows regular maintenance to the exterior of the housing structures and to the drainage components.

VI. SPECIALIZED SUPPORT FACILITIES

A. Quarantine

Quarantine facilities are used to separate newly imported animals or animals with communicable disease conditions from others in the colony. The quarantine facility should be located away from other animal housing and support areas, but be accessible to vehicles to transport animals to and from the centralized facilities if necessary. Whenever possible, support functions such as cage-washing, radiology, etc., should be included in the quarantine facility to eliminate the possibility of exposing quarantine animals to others. The facility should be located on a separate road, which will allow access by truck without the need for entering the main gate on campus, if necessary.

Several design elements should be incorporated in quarantine facilities to enhance containment practices and increase compliance for containment protocols as described by the Centers for Disease Control and Prevention. A procedure/processing room should be designed near the loading dock to process shipments of animals as they first arrive at the facility, in order to keep them separated from the animal housing areas. Ill NHP can then be quarantined within a cubicle in the

procedure room until further assessment of their condition allows them to be moved with the rest of the animals in the shipment. A two-corridor system in the facility will allow for the movement of newly imported animals from the loading dock through an airlock to a holding corridor while animals released from quarantine will exit through the procedure room to the procedure corridor and out of the airlock to their final housing area for use in research protocols.

NHP in quarantine are routinely examined, and samples are collected for parasitology, virology, bacteriology, complete blood counts and serum chemistries. In addition, ill animals may require additional diagnostics and therapeutic intervention. Since shipments of NHP into quarantine should be separated at all times, quarantine facility design should attempt to eliminate common-use procedure areas. One way this may be accomplished is to provide a separate small procedure room for each housing room. These procedure rooms can be equipped with storage space for personal protective equipment (PPE), counter tops, examination tables and examination lights for use in examining and collecting samples from ill animals. The addition of a biosafety cabinet in the procedure room will allow animals to be examined and tissue samples to be collected in the cabinet, further enhancing biocontainment (CDC, 2007).

A radiology suite for thoracic radiography and for other diagnostics should be built into the facility in order to prevent the need to transport animals to centralized radiology facilities, which might result in exposure to other animals. Likewise, a cage-wash facility and cage-washer should be incorporated in the building design to alleviate the need to move contaminated caging to other areas for cleaning.

While not required under ABSL2 containment, an autoclave large enough to accommodate caging should be considered in case the need should arise for sterilization of caging equipment prior to cage-washing. Use of the autoclave for animal wastes and equipment can be implemented along with personnel protocols if ABSL3 containment is necessary, such as in the event of an epizootic with an infectious agent. The addition of design features that enable the facility to operate under ABSL3 containment practices enhances the biosecurity of the NHP colonies.

As elsewhere in NHP facilities, access to the quarantine facility should be limited to essential, trained personnel. Access to the animal housing and procedure areas should only be provided through the change/shower rooms, which encourages individuals to use the appropriate PPE prior to entering the facility.

A line drawing of a typical quarantine facility which incorporates all of the described design features can be seen in Figure 21-27.

B. Nursery

Nursery facilities should be designed to support research programs using neonates and infants, as well as to support animals from the breeding colony. The design differences for nursery construction are based on the need to separate animals with differing pathogen status, provide different environmental conditions than for adult NHP, and enhance the provision of enrichment.

Depending on the size of the program, multiple small housing rooms or divided housing rooms should be available for NHP with differing disease or pathogen status. These different areas can also be used for housing animals of different ages, which require different levels of care. Specific attention should be given in the design phase to provide for social housing and environmental enrichment for infants and juveniles, since NHP of this age are at a critical stage of social development. As for adults, many of the social housing needs are met by using caging specifically designed for this purpose, but the design of animal holding rooms should provide space for these housing configurations. If infants will be moved daily for short intervals of time for social housing during the early phases of socialization efforts, the rooms for socializing and housing the animals should be in close proximity. As infants age and are socialized in larger groups and with adults, movement to larger group housing indoor facilities or runs is helpful for the process. Having these areas associated closely with the nursery helps in the transition, and allows trained personnel to stay in close proximity.

Because of the varied types of critical monitoring and support equipment necessary in the nursery, many electrical outlets with emergency power protection are required in housing areas. Since each cage may require power for heating pads and monitors, multiple outlets may be required at each cage site. Incubators may be required for neonates, and power sources should be present for these needs. Neonatal and infant NHP require smaller caging, which allows more caging to be placed in a specified area when compared to adult housing areas.

The nursery suite should include a food preparation area for special diets and formula preparation. This area should be in close proximity to the housing area because of the need to prepare these items many times each day. Refrigeration should be provided in this area for perishable items, and ample food storage facilities should be available for non-perishable food items. The food storage areas should be close to the housing area, since these items are used in large quantities on a daily basis. Dedicated laundry facilities should be present to accommodate the large bulk of linens that are changed several times each day for each animal.

Environmental controls for nursery housing rooms should be able to be adjusted and monitored independently, as neonates and infants require higher temperatures in their housing rooms than do older NHP.

C. Food Storage

In order to streamline daily operations, facilitate delivery and help assure quality, food storage facilities should be centralized. The temperature-controlled facility should be

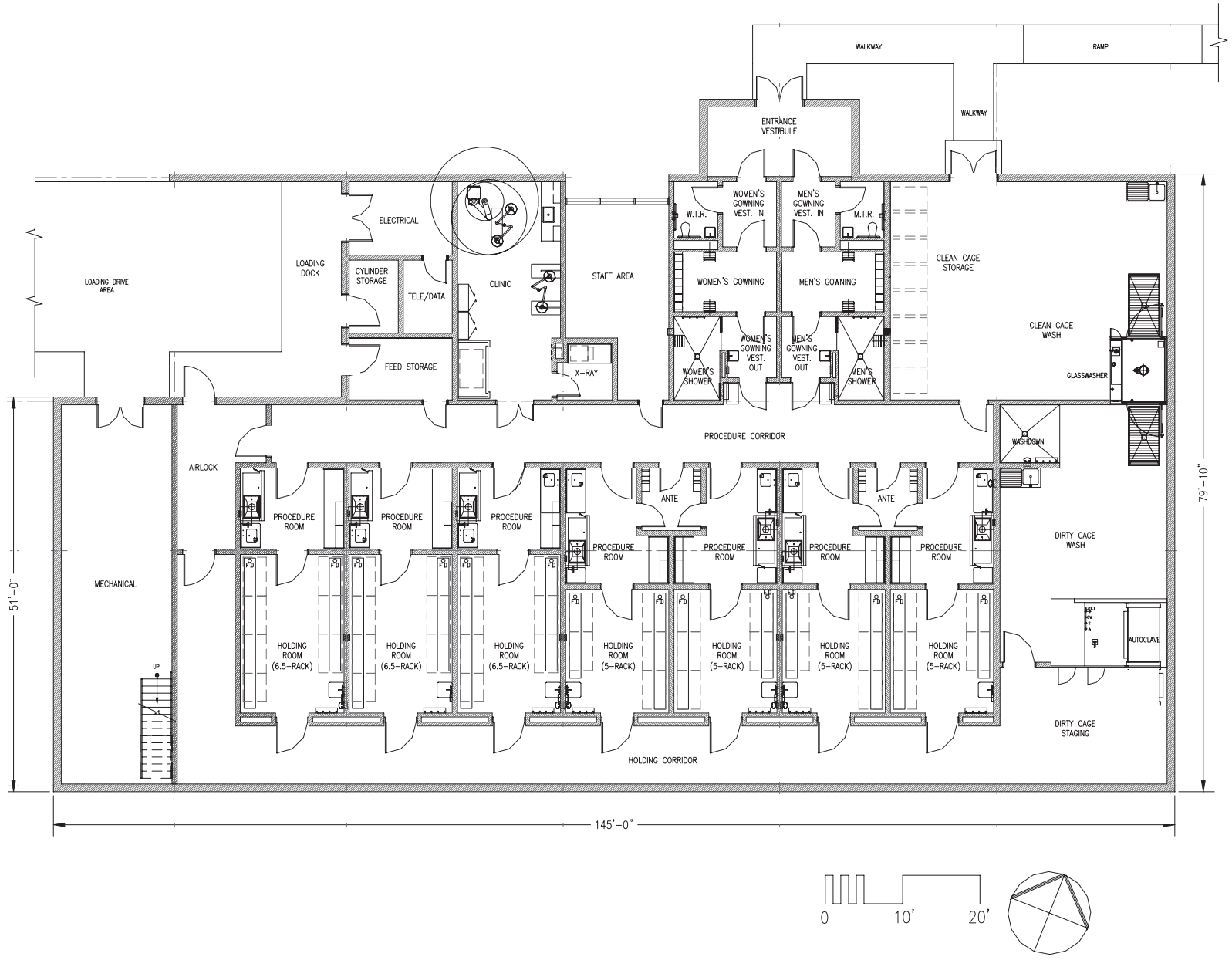

Fig. 21-27 Line drawing of quarantine facility.
The line drawing of a typical quarantine facility housing NHP includes multiple procedure rooms, housing areas, loading dock and other support features.

accessible to delivery trucks, and be sized to accommodate at least two full loads of food to allow for rotation of stock. Capacity can be built into the facility to provide space for storing additional food in the event of a natural disaster which might preclude timely delivery of food. Depending on the size of the facility, a loading dock should be constructed to accommodate large trucks so that food can be offloaded using forklifts or similar equipment. In facilities that are spread over large areas, it may be preferable to build several central facilities. Providing separate rooms for separate shipments is not necessary but preferable. Construction and finishes of the facility should replicate that in animal housing areas. Separate doors should be present for unloading food shipments and for personnel access. Animal-care personnel should be able to access the centralized facility daily or as often as necessary to supply the individual smaller food storage areas in each of the NHP housing facilities. Storage facilities for produce should be available, and can be incorporated in the centralized food storage facility in separate rooms. Storage of produce and other enrichment items usually requires freezing and/or refrigeration. These rooms should be separated from the larger food storage rooms because of the heat generated from such appliances. The food storage facility should be temperature controlled, and be monitored by the centralized environmental monitoring system.

D. Cage-Wash Area

The cage-wash areas should be built to industry standards and requirements defined in the *BMBL* for ABSL-2. As in other laboratory animal facilities, both clean and dirty cage-wash areas should be available. The same parameters used in cage-wash design and construction for other species apply to NHP facilities. As previously stated, the large size of some NHP caging systems requires larger doorways and large amounts of storage space for both clean and dirty caging. A large area should be devoted to spray-down of cages prior to entering the cage-wash, and can be accommodated by constructing a drainage pit with a grating. If adequate storage for clean and dirty cages cannot be accommodated in the cage-wash area, then separate storage areas can be constructed adjacent to the cage-wash facility to accommodate extra caging. These storage areas must communicate with the corresponding clean and dirty sides of the cage-wash to retain the separation between contaminated and clean caging. The cage-wash and attached cage-storage areas should be able to accommodate at least one full animal room of caging to allow for efficient change-out. Often, space for two or more rooms of caging must be available in large facilities that require changing-out several rooms in a day.

If an automatic watering system is constructed on the caging racks, a chlorine injector system may be required for disinfection of these systems. This equipment can be placed in the cage-wash building.

As in other parts of the facility, all hardware and mounted equipment should be protected from inadvertent damage from rolling cage rack systems.

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Chapter 22

Facilities for Dogs, Swine, Sheep, Goats and Miscellaneous Species

Donald B. Casebolt

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I. GENERAL CONCEPTS AND DEFINITIONS

The housing methods used for dogs, swine, sheep, goats and miscellaneous species will be partially dependent on the specific research protocol on which the animals will be assigned. However, the issues presented in this chapter will provide guidance to those intending to design facilities for general use, with comments on specific areas that may influence design for certain research protocols. The grouping of dogs, swine, sheep and goats is based primarily on the size of the animal, husbandry requirements and facility needs, which are often similar for these species regardless of the disparate types of research protocols on which they may be assigned. Swine and small ruminants are included in this chapter in the context of their frequent use for certain types of biomedical research outside the realm of agricultural production research. This chapter will not discuss the use of these species for agricultural research, but will discuss facility design issues with the assumption that the facility is

part of an animal-care and -use program supporting biomedical research associated with a multi-species vivarium. For example, outdoor housing will be discussed, but with the assumption that animals will also be accessed within an indoor animal research facility for procedures relating to the biomedical research protocol. Guidelines for agricultural animal research are available (FASS, 1999). Other miscellaneous species may have significant differences in cage size, preferred environmental conditions, and other parameters pertinent to animal facility design. However, these diverse conditions can be met within the same animal facility if flexibility is considered throughout the facility design process.

II. REGULATORY ISSUES

A. Structural Environment

The Laboratory Animal Welfare Act (Pub. Law 89-544) regulates dogs specifically, as well as "any other warm-blooded animal, which is being used, or is intended for use for research, teaching, testing, experimentation, or exhibition purposes…" These regulations also exempt "farm animals, such as, but not limited to livestock or poultry used or intended for use as food or fiber, or livestock or poultry used or intended for use for improving animal nutrition, breeding, management, or production efficiency, or for improving the quality of food or fiber." These regulations would then exempt swine, sheep and goats if used for these other non-research purposes and when housed in the context of agricultural production or production-related research. However, these regulations do cover swine, sheep and goats when housed in research, teaching and testing facilities. There are no specific regulations written for these species, such as requirements for specific cage size, social environment or exercise. For this reason, housing facilities for larger animals are often designed primarily for canines, with flexibility to include other species.

Public Law 89-544 has specific requirements for canine housing, including minimum floor space calculated by taking the mathematical square of the sum of the length of the dog (from the tip of its nose to the base of its tail) plus 6 inches, then dividing the product by 144. Additionally, the interior height of primary enclosures for a dog must be at least 6 inches higher than the head of the tallest dog when it is in a normal standing position. Further, the regulations have specific requirements for exercise of dogs to be determined by the attending veterinarian in consultation with the Institutional Animal Care and Use Committee. Exercise can be provided in a variety of ways, including group-housing dogs in compatible groups, individually housing dogs in cages, pens, or runs that have twice the floor-space requirement as calculated above, or providing access to a run or open area for exercise at a frequency and duration to be determined by the attending veterinarian.

These requirements focus on the individual canine, which may be problematic when designing facility space with the flexibility to house dogs and other species of various sizes and weights. For this reason, most facilities design housing situations for canines that take into account the requirements for the largest animal that might be housed, and apply this standard as the single cage or run size (or multiples of that size) throughout the facility. Additional requirements for dog housing as outlined in the *Guide for the Care and Use of Laboratory Animals* (the *Guide*) (ILAR, 1996) list a floor-space requirement of equal to or greater than 24 square feet for dogs weighing over 30 kg. Applying the Animal Welfare Act formula requirement in reverse to a large-breed dog that is singly housed in a 24-square-foot pen or run yields a maximum length from the tip of the nose to the base of the tail of 35.5 inches. Because dogs larger than this would be uncommon in most laboratory animal facilities, the Animal Welfare Act and the *Guide* can be harmonized in nearly all facilities by housing all dogs in pens or runs that are 24 sq. ft (typically 4' × 6' in dimension) even if facility or research requirements necessitate single housing of animals. Flexibility to increase floor space in order to house individual larger canines, temporarily or permanently pair- or group-house animals, or provide larger exercise spaces, is accomplished by placing doors or gates between runs within a room. Additionally, pairs or groups of smaller canines (for example, beagles) weighing less than 30 kg and requiring 12 square feet of floor space, according to the *Guide*, are easily accommodated within the same format (for example, pair-housing in the same 24-sq. ft run). However, a facility that is highly committed to a research program with large numbers of a standard smaller dog breed such as the beagle might elect to standardize cage or run floor space to 12 sq. ft, realizing that flexibility to house larger breeds might be limited unless cages or runs can be combined to create 24-square-foot or larger spaces.

There are no specific requirements outlining cage space for sheep, goats or swine in the Animal Welfare Act Regulations. For this reason, facilities must rely on *Guide* recommendations alone for housing these species. Similar issues of flexibility should apply to housing these species, typically in pens or runs that are of a standard size selected by the facility management staff. However it is equally important to consider flexible floor space increases through the use of removable panels between runs or pens for these species. Small ruminant species with strong flocking instincts should be housed in larger groups when at all possible to maximize behavioral enrichment. The use of 24-square-foot runs may be acceptable for these species, but differing floor-space requirements in the *Guide* would necessitate larger floor spaces for groups of animals. For example, single-housed swine up to 100 kg in weight require 24 sq. ft of floor space according to the *Guide*, while swine housed in groups of two to five animals require 20 sq. ft of floor space for each animal and could be accommodated in 24-square-foot runs in groups if panels between runs can be removed.

Similarly, floor spaces for miscellaneous species may be dictated by regulatory requirements. Certain species (such as rabbits and cats) may have specific regulations or guidelines relating to caging size and design, room environmental requirements, or other issues pertinent to animal facility design. However, other species (such as ferrets) may be covered by regulations and guidelines in only a general sense, without any specific guidelines relating to housing methods. In cases such as this, facility veterinarians and managers must base facility decisions on what may be common practice in the literature or in other facilities housing this species.

B. Social Environment, Exercise, and Other Behavioral Management Issues

As required by the *Guide*, the social and behavioral environment must be addressed for all species. Because the species discussed in this chapter are all social animals, there is a direct relationship of these issues to those discussed above relating to run or pen size, flexibility to expand to larger floor spaces, and group-housing of these species. Some experimental protocols require individual housing of animals, or individual housing may be necessary for veterinary or behavioral reasons. If this is the case, the social requirements of these animals may be addressed by other methods. Examples include design of facilities and holding runs of pens that allow visual contact, auditory contact or olfactory contact for animals through the side panels of individual enclosures. In addition, the enclosure should allow for ease of access by animal-care staff for socialization with humans as part of the behavioral management program.

The ability to conveniently open and close doors between enclosures is also a useful tool to allow temporary pair- or group-housing, with separation of the animals when required by experimental design. These issues have led to changes in facility design philosophy over the past two to three decades. For example, in the past many facilities designed for canine housing were constructed with partial walls of solid masonry block between individual runs. The more stringent requirements for social housing have resulted in a preference for alternate designs allowing for a greater degree of social housing and exercise. Similarly, the Animal Welfare Act Regulations have specific requirements for exercise of dogs. In addition to the floor-space requirements for animal housing mentioned above, certain components of canine holding systems have advantages in meeting these requirements. For example, pens or runs that allow opening and closing of divider gates can be used to create a larger exercise pen, or pens and runs may be constructed to open easily into exercise areas or hallways if desired as part of the institutional program.

Additional aspects of enclosures to consider are the ability to conveniently add or remove items such as resting boards or other devices that may attach to the pen or run for social and behavioral management reasons (Olfert *et al*., 1993).

III. FACILITY DESIGN AND CONSTRUCTION CONSIDERATIONS

A. Housing Configuration

Larger species are often housed outdoors in their natural environments when not used for research purposes. Because of this, housing configurations for these animals may include a component of outdoor housing. All of these species could be housed completely outdoors with appropriate shelters, or with a combination of indoor and outdoor housing. Certain species, especially small ruminants, are frequently housed partially outdoors as part of the behavioral management program as discussed above. For example, group-housing of small ruminants in larger outdoor pens or pasture areas would allow for more extensive species-typical flocking behavior. However, the ability to access individual animals easily for research manipulations, individual animal monitoring and procedures such as sample collection, administration of drugs, or surgery usually dictates that animals are housed inside. Facility design should allow for efficient movement of animals from outdoor to indoor areas. It is also important to consider the impacts of environmental changes not easily controlled, such as temperature, humidity and light levels, on animals housed completely or partially outdoors. In addition, the health and disease status and health surveillance issues relating to these animals would present additional concerns due to possible exposure to wild birds, rodents or other species that are not as easily excluded from outdoor or indoor/outdoor areas. Finally, security and public relations issues associated with larger species used for biomedical research often preclude their housing in outside environments within view of the general public. For all of these reasons, outdoor and indoor/outdoor housing configurations are becoming much less prevalent. If these configurations are included in the facility design, it is important to consider these issues.

As indicated above, this chapter assumes that the facility design is oriented towards the accomplishment of biomedical (not agricultural) research. For this reason, housing configurations are discussed in more detail in the context of an indoor housing facility. Runs or pens within an indoor facility are typically of a standard size, such as 4' wide by 6' feet deep to allow for a 24-square-foot floor space, as discussed above. Using this enclosure size as a common example, facility designers and architects can establish the orientation and placement of enclosures within an animal housing room. Typically, runs are oriented directly against the side wall or walls of the room, with an allowance of at least 4'–6' feet between the front door of the enclosure and another wall surface or run. This distance is dependent upon the type of entry door (swinging or sliding) into the enclosure and other types of equipment used within the room, such as transport carts. In any case, these dimensions would necessitate a room width of

between 10 and 12 feet for the orientation of a single row of 6'-deep runs along a single wall. Similarly, room widths of at least 16'–18' are required for a double row of 6'-deep runs oriented along two side walls. These dimensions assume that the back walls of the runs are placed directly against the side wall, or that the wall surface actually forms the back of the run. However, if possible, it is recommended to space runs away from the wall for reasons discussed in the next section, and these clearances then must be included. For example, spacing runs 18" away from each side wall increases the needed room width by an additional 3' for a room configured with two rows of runs and a central aisle.

B. Cage and Pen Configuration for Dogs, Swine, Sheep and Goats

There is a wide variety of caging systems available for housing large animals. While much of the discussion in this chapter focuses on the use of runs, many facilities prefer either freestanding cages or cages fixed within the animal room. In particular, the use of freestanding cages allows for some flexibility in animal room configuration, because caging panels can be completely removed from the room and washed in a cage-and-rack washer. However, the regulatory issues discussed above must be considered more carefully, especially in the context of exercise for large animals such as dogs, which may need to be moved to an exercise pen or run in order to meet the requirements of these regulations. Within the general framework of caging systems possible for housing large animals, it is therefore most common in contemporary animal facilities to see these species housed in runs (Mench and Krulisch, 1990). Runs may be of various types, including those that are attached permanently in the room, although it is more common to see prefabricated, freestanding runs or pens either standing directly on the floor surface, typically with bedding materials applied directly on the floor (Figure 22-1), or with grated or slatted floors raised above the room floor surface (Figure 22-2). Runs may be attached to side walls of rooms, such that the wall forms the back wall of each run. However, as mentioned above, it is advisable to provide a back wall for the run if possible, rather than using the room wall, in order to avoid increased maintenance of wall surfaces damaged by animals, and possible loss of wall-surface integrity and sanitation efficiency by bolting or otherwise attaching runs to the wall surface. A distance of 18" inches from the back of the run to the room wall has been recommended (Hessler and Leary, 2002) to allow for an access aisle to a trench drain behind the runs. An even wider working space may be desirable in this location, although the space available for this purpose may be partially dictated in the design by total wall-to-wall width available in the room. Distances of as little as 6"–8", while not ideal, will separate animals from direct contact with wall surfaces.

Fig. 22-1 Chain-link runs within an animal housing room with a single, capped floor drain. The runs are 4' × 6' in dimension, with the 6'-long back panel oriented along the side wall of the room to provide a larger aisle between runs. The runs are equipped with fiberglass resting boards and direct bedding consisting of wood shavings.

Fig. 22-2 Stainless-steel runs constructed of a combination of tubular materials and mesh on the upper panels with raised fiberglass slat flooring panels. The runs are 4' × 6' in dimension with sliding gates between the runs allowing for pair- or group-housing of adjacent animals as needed. The room is configured for wet sanitation with a trench drain and flush mechanisms (not visible) located behind the runs and a central ceiling-mounted hose reel.

Runs may be constructed of a variety of materials. Galvanized chain-link runs are readily available at low cost, but are not as durable as those made with stainless-steel panels constructed of sealed hollow bars, tubes or mesh materials.

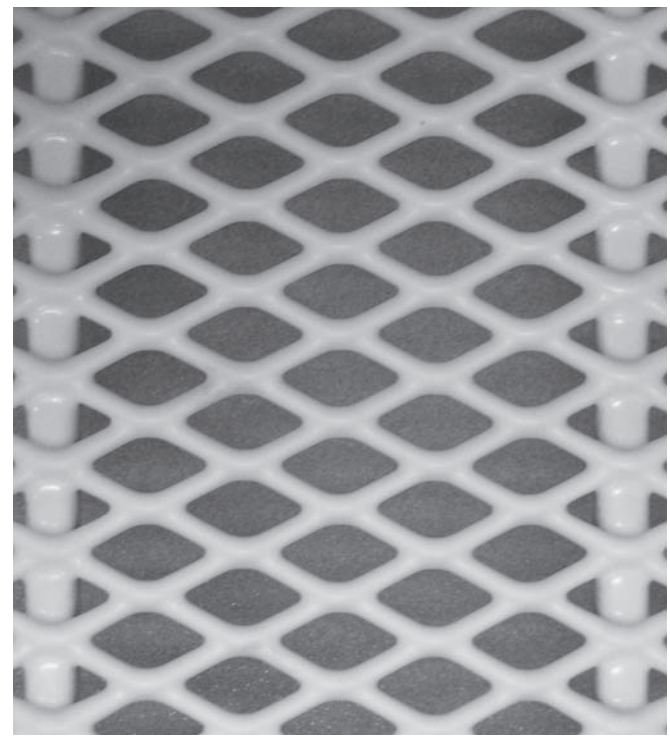
Depending on the degree of separation desired between animals, and behavioral management issues, solid composite panels constructed of various materials are available. These materials include stainless steel, fiberglass-reinforced panels, polyvinyl chloride foamboard, acrylics, and high-density plastic laminates and other related materials (Hessler and Leary, 2002). These types of materials are also often used for resting boards, due to their lower rate of thermal transmission and their comfort and sound-attenuating properties while maintaining a high degree of sanitizability (Mench and Krulisch, 1990).

If freestanding or partially attached runs are utilized with raised floors, there is a variety of two general types of flooring materials used. Two commonly used materials are either expanded metal flooring panels which are coated with polyvinyl chloride (Figure 22-3a), or reinforced fiberglass slatted panels (Figure 22-3b). Expanded metal panels may be constructed of polyvinyl chloride-coated steel. However, panels constructed of polyvinyl chloride-coated aluminum are much lower in weight and therefore more easily handled by animal-care staff (Mench and Krulisch, 1990). The degree of openings in panels should be considered. For example, fiberglass panels are available in various widths of openings between slats. Openings of half-an-inch are recommended for hoofed animals, because it is less likely that hooves will become caught in the opening. Similarly, smaller openings in coated, expanded-metal panels are advantageous to prevent dog toes from becoming entrapped. This is balanced with the purpose of providing the openings within floor panels to allow urine and feces to drop through the panel easily. Additional issues to consider in floor-panel selection include the species housed. For example, fiberglass slats with a higher degree of texture on the surface are desirable for small ruminants and swine in order to improve footing on the surface and prevent overgrown hooves. However, the texture must not be so rough that it may result in skin or hoof abrasions, or become difficult to clean and sanitize effectively. In the case of canines, the flooring type may be a consideration in prevention of entrapped toes, broken toenails or interdigital cysts. In one study (Kovacs *et al*., 2005), the authors found that the incidence of interdigital cysts in beagle dogs was significantly higher in dogs housed on flat-bar polyvinyl chloride-coated floors compared with flat-bar uncoated stainless-steel or diamond-shaped expanded-metal polyvinyl chloride-coated floors.

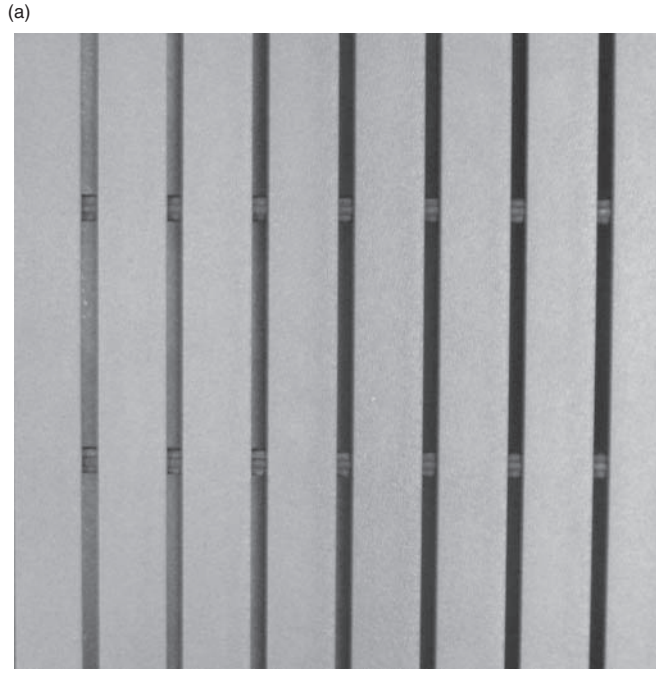
Cubicle housing is available in many animal facilities, and is a useful alternative for housing large animals in small numbers or individually. In many cases the cubicle itself may be both the primary and secondary enclosure for the animal, with either dry bedding materials provided or wet sanitation methods employed, depending upon the availability of floor drains. The subject of animal isolation cubicles is covered in Chapter 15 of this book, and in previous references (Hessler, 1991).

C. Cage and Pen Configuration for Miscellaneous Species

The configuration of housing rooms and primary enclosures for miscellaneous species is, of course, highly dependent



(a)



(b)

Fig. 22-3 Examples of flooring materials for raised-floor large animal runs. The most common types are expanded aluminum with (a) polyvinyl chloride coating and (b) fiberglass slats.

upon the species and research use. In addition, environmental controls must be capable of providing a broad range of temperature and humidity levels depending on the needs of the species to be housed. Construction materials and sanitation procedures should stress flexibility, because certain of these species may be housed without a primary enclosure *per se* (that is, within the animal room itself), meaning that the room floor and wall surfaces may be directly exposed to animals. The most common examples of this type of housing are for cats and rabbits (Olfert *et al*., 1993; Reinhardt and Gluck, 1997). Cats are frequently held directly in small to medium-sized animal rooms with litter boxes directly on the floor and other items, such as perches, located within the room. Alternatively, rooms may be equipped with large group pen enclosures. Similarly, rabbits have been housed in floor pens, typically with direct bedding. While individual housing is absolutely required for some rabbits, such as mature bucks, compatible groups of rabbits can be housed in groups. Group-housing methods such as these have been cited as examples of methods to provide a highly socialized and enriched environment for cats, rabbits and other species (Olfert *et al*., 1993). Rooms used for this type of housing should be designed with very durable, moisture-resistant surfaces, such as those commonly used in large animal rooms or cage-washing areas that may be exposed to moisture. Sanitation procedures used for animal care may also have a significant impact on the design of animal rooms for these species. For example, if rabbits are housed in floor pens, it becomes desirable to have the room equipped with a floor drain and hose bib or hose reel for wet sanitation at defined intervals.

D. Environmental Control

Because larger species are typically housed in open runs within an animal room, the environmental conditions within the room as a whole are those to which the animals are exposed. Recent versions of the *Guide* have allowed for some flexibility in air exchange rates within individual rooms. However, these recommendations are based partially on the fact that special ventilation systems for rodents, such as individually ventilated racks, may provide additional beneficial impacts on the environment that the animals experience. For this reason, traditional air exchange rate minimums of 10 air changes per hour are still usually applied to large animal facilities. This is discussed in some detail in other chapters. Exhaust air exchange rates are critical, since large animal rooms are usually balanced at negative static pressure for odor- and allergen-control purposes.

Air plenum design and placement is an important consideration. Many guidelines recommend placement of exhaust plenums low on the wall, with supply plenums on the ceiling. This allows for exhaust flow across or through the animal enclosures, and is thought to reduce dander circulation within the room. Additionally, low exhaust plenums near an animal run do not expose animals to drafts to the extent that supply plenums would. However, the placement of wall exhaust plenums should be considered in the overall facility design, because the thicker wall thicknesses to accommodate ducting will reduce the overall size of animal rooms by a small amount and affect the efficiency of overall facility space utilization. For this reason, many facilities are designed with ceiling supply and exhaust plenums which, despite possible advantages of low wall exhaust, provide adequate ventilation. It may be desirable to design facility rooms with large animal runs in place, then consider the placement of supply and exhaust plenums in the rooms to optimize ventilation efficiency.

Another unique aspect of facilities for larger species is the consideration of waste handling by wet methods, which may significantly increase humidity levels immediately following room cleaning. However, excessive humidity due to wet sanitation methods can usually be controlled by adequate drainage of moisture after sanitation and by adequate exhaust ventilation, making the elevated humidity following sanitation a temporary phenomenon.

E. Noise Control

Noise control is a major issue, especially in facilities housing large numbers of canines or swine. It is important to control noise both for the purposes of worker safety and for animal welfare reasons. To the greatest extent possible, facilities should separate animals that produce significant noise from those that may have stress reactions to that noise. Sound levels in dog kennels can reach levels of 85–122 decibels (Peterson, 1980). In many cases, dog barking may be a behavioral management issue that can be addressed by modification of the primary enclosure or providing noise-abatement devices within the room or facility. Sound-abatement devices are available to be mounted within animal rooms, and partially absorb noise. However, the possible difficulties in sanitation of such devices must be considered. For this reason, it is preferable to address noise control within the context of facility design, and it is advisable to employ an acoustical engineer during the design process. Additional redundant wall surfaces, acoustic doors, and cavity walls and ceilings with insulation can provide a significant degree of noise control. In addition, corridors can carry noise for significant distances, and should be included in the noise-control plan (Reinhardt and Gluck, 1997).

F. Sanitation Procedures

A major decision in facility design for large animal housing and for some miscellaneous species is whether sanitation will be accomplished by wet or dry methods. However, the “dry” method always includes a “wet” method of management. This essentially necessitates at least one floor drain within the room, and a hose bib or hose reel located within the room,

regardless of the management type used. It is not advisable to attempt large animal housing in a room without a floor drain or drains (Hessler and Leary, 2002).

In the dry sanitation method, bedding materials are supplied directly on the floor surface of the animal room within floor-mounted runs. Waste materials are handled as soiled bedding, which is typically "spot cleaned" on a once or twice daily basis to remove feces and urine-soaked bedding. Bedding is then disposed of as solid waste. At some interval, animals are completely removed from the runs and room, all bedding materials are completely removed, and the floor, wall and run surfaces are thoroughly sanitized by a wet method such as scrubbing, mopping and/or high pressure sprayer with detergents and disinfectants. Typically, these procedures are performed once a week or once every 2 weeks. Regulatory requirements for dogs and cats covered under the Laboratory Animal Welfare Act (Pub. Law 89-544) specify that these procedures are performed at least once every 2 weeks. The use of dry waste management simplifies the facility design relative to floor drains. For example, a single floor drain can be placed in the center of the room (between the runs), and the drain can be of a smaller diameter (such as 4" inside diameter instead of 6" inside diameter). Drains should be equipped with a cap so bedding materials do not enter the drain during dry management procedures and clog it. It is always advisable to have some slope towards the floor drain, but a single drain per room greatly simplifies the engineering of floor slopes and allows for a lesser slope in a given area of the room.

Wet management procedures necessitate careful planning of floor drainage systems and slopes of floors towards drains. In wet management systems, bedding materials are not used. Animals are housed either in floor-mounted runs directly on the floor surface or, more commonly, on raised, partially open floors above the room floor surface. Urine and feces fall through the partially open raised floor surface in order to keep the animals relatively dry and clean. On a once- or twice-daily basis, wet management rooms and runs are cleaned by scrubbing, mopping and/or high pressure sprayer with detergents and disinfectants.

The efficiency of the wet management process is highly dependent on the proper layout of floor slopes and drains and the availability of a high-pressure hose bib or reel within the room. The most efficient room layout for this process is the placement of a trench drain along the side and/or back walls of the room, within which a floor drain or drains are located (Figure 22-4). Floor drains of 6" inside diameter are preferable and recommended in the *Guide* and by others (Olfert *et al*., 1993; Hessler and Leary, 2002). The raised floor runs are then positioned such that the back of the run is located over or at the edge of the trench drain. Floor surfaces must be carefully planned so that areas under the runs slope towards the trench drain. This slope is typically at least one-eighth inch to three sixteenths inch per foot (1–1.5 percent slope). In addition, the surface of the trench must slope towards the drain, usually

Fig. 22-4 Trench drain along the side wall of an animal room equipped with a central rim flush floor drain (outside bottom of photograph) and water jets at both ends to flush waste towards the drain. A wall-mounted hose bib is available in the room.

located at the center or end of the trench. The slope of this surface is ideally at least 2 percent (Hessler, 1991; Hessler and Leary, 2002). Additional useful features of trench drains are flush mechanisms to introduce water flow from the ends of the trench towards the drain, and rim flush mechanisms within the drain to insure sufficient water flow within the drain itself. Depending upon the size of the rooms, the degree of slope on floor and trench surfaces, and the pitch of pipes towards main sewage lines, there may be significant depth needed for plumbing below the actual floor surfaces of the rest of the facility that needs to be considered early in the facility design process.

As mentioned above, the decision relative to the sanitation method(s) to be employed is a critical factor to consider early in the design of a facility if significant numbers of large animals are to be housed. Design of the facility for wet sanitation is highly recommended. However, dry sanitation methods do offer some advantages, including simplification of the design of room floor drainage systems with a less significant depth below floor surfaces for sanitary sewage lines. In fact, dry sanitation may be the only alternative for retrofitting general animal holding rooms for large animal housing, if those rooms are not

equipped with trench drains. There are obvious advantages of lower ongoing costs for water and sanitary sewage disposal. The use of bedding materials can become a part of the overall facility plan for environmental and behavioral enrichment for large animal species by providing bedding materials that animals can rest upon, and also by possible inclusion of bedding as a foraging behavior tool, for example (Reinhardt and Gluck, 1997). Bedding also allows for improved footing and lowered slipping problems on floor surfaces for hoofed animals. The disadvantages of dry sanitation methods are the cost and handling issues relating to large volumes of bedding materials, dust, allergen exposure, and staff ergonomic issues during the handling of large amounts of bedding, and the usual necessity to completely empty the animal room at some interval to provide complete room sanitation by wet methods. Wet sanitation has disadvantages of higher water and sewage disposal costs. Also, there are possible worker safety issues, as discussed below.

G. Construction Materials and Surfaces

Construction materials and surfaces are discussed in detail elsewhere in this text. However, as a general principle, if the facility may be used for housing large animals, there should be careful consideration of the construction materials and surfaces to be used in rooms. As mentioned above, large animal housing involves more direct contact of animals and animal excreta with animal room surfaces, which necessitates the construction of surfaces that are able to withstand possible direct animal contact, excreta, cleaning and disinfection agents, and water on a more frequent basis than in animal rooms housing smaller animals in cages. As mentioned above, even "dry" sanitation methods for large animals involve a component of "wet" room sanitation on a frequent ongoing basis.

H. Flexibility

Animal facility flexibility issues are especially important when designing housing for large animals and miscellaneous species. It is difficult or impossible to retrofit a facility to provide the upgraded surfaces required, and items such as floor drains or trench drains absolutely must be included in original facility design in order to accommodate large animals. For this reason, consideration of the possible inclusion of large animals in the research program is necessary early in the facility design process, and specific design features must be incorporated into large animal rooms if their use is contemplated. Conversely, while floor drains or trench drains may not be desirable in a room housing rodents, a room originally designed for large animals can more easily be retrofitted for rodent housing if the runs or pens are not permanently fixed to room surfaces and can be removed, and if covers are available for floor or trench drains (Figure 22-5). In general, some large animal housing space should be specifically included in an animal facility design if the use of these species is possible in the future research program, with flexibility in design to allow for other uses if necessary.

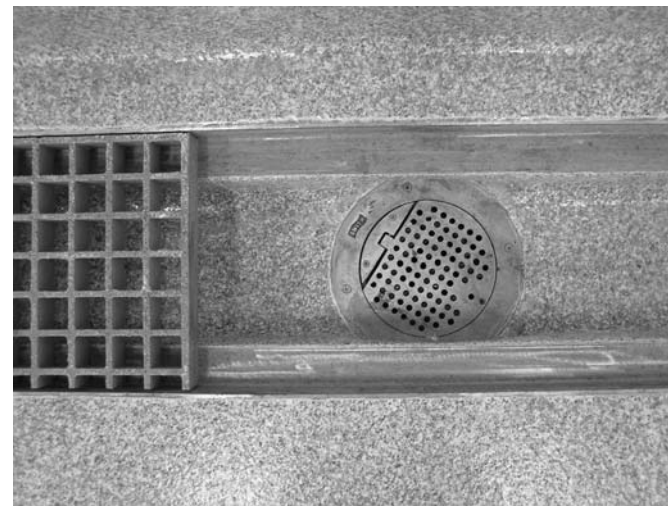


Fig. 22-5 An example of a rim flush floor drain designed for high volume wet sanitation. The drain is covered with a brass grate cover and the trench can be covered with fiberglass grates (partially covered on the left of the figure) to allow for flexibility in room use.

I. Safety and Staff Ergonomic Issues

Occupational health and safety are discussed in detail in other sections of this text. Because of the larger size of the animals and related sanitation issues as discussed, there are unique occupational health and safety issues that should be considered in designing large animal housing facilities. For example, experimental manipulations or movement of animals from holding areas to procedure areas may involve lifting of animals, which can be minimized or avoided through the use of hydraulic or electric lift devices available for animal care. If animals are housed in runs that are elevated above the floor surface, devices should be considered to height-adjust to run floor-level, and ramps or other means may be important if animal movements are frequent. An additional consideration in deciding what sanitation method to use is the possible occupational health issues associated with each method. For example, dry sanitation will necessarily involve bending and lifting for staff members to pick up waste materials on a daily basis, and transportation of solid waste containers to the location of final disposal. Dust and possible concentration of animal allergens in bedding materials should also be considered. Conversely, wet sanitation will involve possible increased exposure to aerosolized materials, increased wet surfaces and slipping hazards, and other ergonomic hazards such as those associated with operation of hoses and spray equipment. During the facility design process, these possible hazards and methods of minimizing their impact should be considered (National Research Council, 1997).

J. Adjacency and Security Issues

In addition to considerations of the room design, large animal housing areas should be designed with attention to issues of adjacency to other areas of the research facility and security of the animals and staff members. Ergonomic issues relating to the movement of large animals were mentioned in the previous section. One method to mitigate this impact is to locate large animal housing rooms near procedure areas, surgical suites and other areas within the animal research facility to which these animals may be moved. This might involve creation of a large animal suite or section of the facility through which other animals or staff members not involved in large-animal care and use are allowed access. Similarly, loading areas for incoming animals should ideally be located near the large animal housing areas to minimize traffic of these animals through other areas of the facility, and routes for waste disposal should ideally be separated as well. Therefore, in general, the differing management methods used for these species, adjacency needs and noise levels generated dictate that the ideal housing location should be physically separated from other species to the greatest extent possible (Hessler and Leary, 2002).

There are continuing and more serious security concerns relating to the use of all animal species in research, teaching and testing. However, there are often heightened public concerns for species, such as dogs, that are maintained as pet animals. The same principles discussed to minimize traffic to other facility areas can be used to maximize security of areas for housing large animals by separation of areas and provision of separate locks or electronic devices such as security card readers or other mechanisms to allow only authorized personnel into these areas. In many cases, closed circuit television cameras and recording devices are desirable to document traffic in and out of the areas. Loading dock areas are an additional area of concern relative to security. For example, consideration should be given to the enclosure of loading dock areas with roll-up doors to load and unload animals out of the view of the general public.

IV. CONCLUSIONS

This chapter presents unique features of animal facility design relating to the care and use of dogs, swine, sheep and goats. Many of the design features for these species are similar because of similarities in size. In addition to regulatory requirements that may dictate specific housing arrangements, facility design for these species should include specific components early in the design process because of difficulties in retrofitting existing facilities to incorporate these components at a later date. In particular, the sanitation method or methods to be considered for these species lead to critical facility design decisions.

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Chapter 23

Aquatic Facilities

Helen E. Diggs and John M. Parker

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I. INTRODUCTION

Aquatic animal facilities require special design considerations beyond those of conventional laboratory animal facilities. Water, alone, can cause serious damage to facility structural components through leakage and condensation. The composition, pH and softness or hardness of the water should be considered when plumbing materials and treatment processes are selected. Knowledge of water additives, such as disinfectants, is required for appropriate selection and design of water filtration systems. Water is extremely heavy, and this weight must be factored into the construction of tanks, racks, support structures and transport equipment. Serious personnel injury risks in an aquatic facility include slipping on pooled water and electrocution. Facility design precautions are critical to minimize these hazards.

In January 2005, the National Institutes of Health released a statement saying that

> There has been a dramatic increase in the use of aquatic species (zebrafish, sea urchins, and other marine species), resulting in the adaptation and renovation of older facilities and the potential need to accommodate aquatic species in new facilities

Advancements in aquatic animal research have propelled less traditional vertebrates into the modern era of science, examples being genetically engineered fish (*Brachydanio (danio) rerio*) and frogs (*Xenopus (Silurana) tropicalis*). Only a few species of fish, amphibians, mollusks and echinoderms represent the majority of aquatic animals currently used as research models. Although these species have been used in research for years, aquatic animal husbandry and preventive medicine remains fairly unsophisticated compared to that for commonly used mammalian laboratory animals. It is accepted

that a high percentage of morbidity and mortality of aquatic animals can be attributed to inappropriate captive care. As aquatic animal research techniques continue to evolve, the success of aquatic programs will depend on innovative facility design coupled with an increased understanding of hydrology and aquatic species husbandry and science.

II. HYDROLOGY

A. Water Types

1. *Conventional Water Source*

Water is a complex medium. Small alterations in water's physical and chemical characteristics can have a profoundly negative impact on aquatic organisms. Water that is adequate for human consumption can conceal lethal properties for aquatic life. The quality of aquaria water is dependent on source, treatments, contaminants, husbandry protocols and animal physiology. Incoming water is often incriminated as a cause of morbidity, mortality and spurious scientific results, even without direct supporting evidence. As a result, water quality is a common cause of apprehension for animal-care providers and researchers. A complete analysis and review of local water chemistries and composition, including additives like corrosion inhibitors and algicides, should be performed prior to establishing an aquatic facility system.

Conventional water sources consist of municipal, well and surface water. Proper assessment of water availability is essential to ensure that operational demands can be met throughout the year. For laboratory purposes, surface water is rarely applicable. Well water or underground water, typically offers consistent physical and chemical parameters that primarily reflect the mineral composition of subsurface rock. The ultimate composition of the water is further dependent upon factors such as gas sequestration, geothermal heating and subsurface contamination. As a result, well water can be acidic or contain unanticipated levels of activated ions and compressed gases. Sea water can be natural or artificial (Figure 23-1). Natural sea water may be pumped or transported directly from marine sources. It can also be reconstituted from commercially available sea salts. When pumping natural sea water, the supply intake should be situated off shoreline, distant to inter-tidal zone influences, at depths prohibitive of temperature fluctuations and algae blooms, yet shallow enough to prevent the intake of sediment and biological mass from the sea floor.

Fig. 23-1 Holding tanks for natural and artificial sea water. In this facility, marine water is exclusively carried in polyvinyl chloride (PVC) pipes and all plumbing is exteriorized.

2. *Hardness and pH*

Water hardness is defined as the measured content of divalent metal cations. Dissolved calcium (Ca^{++}) and magnesium (Mg^{++}) are the only two divalent cations found at appreciable levels in most waters. In natural water, both calcium and magnesium primarily exist bound to bicarbonate, sulfate or chloride. When hard water evaporates or is heated above 61°C/141°F, bicarbonate converts to carbonate and precipitates out with Ca^{++} to form calcium carbonate ($CaCO_3$) scale. Levels of water hardness are, therefore, typically reported in mg/l as $CaCO_3$ equivalent, although $CaCO_3$ is not itself present in water. Several classification schemes exist for denoting degree of hardness but in general soft water contains less than 60 mg/l and hard water contains greater than 120 mg/l $CaCO_3$ equivalent. The majority of the United States geography has hard water, while soft water is predominately located in coastal regions. Most tap water originates from local sources, but some municipalities may draw water from multiple – sometimes even remote – locations when necessary. As a result, variations in water hardness or softness can occur within a single municipality depending upon the specific source location and the time of year.

Providing they are acclimated appropriately, fresh-water animals tend to tolerate both soft and hard water within the range typical of potable water. However, morbidity and mortality occur when animals experience sudden changes from hard to soft water. It is imperative to know the hardness or softness levels of the tank water various animals are living in, especially when introducing new animals to a system or transferring them to another system or facility. Additionally, hard-water minerals, such as calcium carbonate, act to buffer pH shifts, while soft water, being lightly buffered, is prone to acidification by acid-forming compounds. Thus, the pH of soft water can be quite variable. Most supply waters have a pH of between 6.5 and 8.0, and the common captive aquatic vertebrates can adapt to water within this pH range.

The effects of water hardness on plumbing materials will vary with mineral concentration, temperature and pH. The

most notorious problems associated with the formation of hard-water mineral deposits are the decreased efficiency and functional longevity of plumbing equipment exposed to heated hard water. Acidic water accelerates corrosion, which shortens the life of plumbing materials and causes staining and discoloration of fixtures. Additionally, most chemicals such as reagents, disinfectants and medications are dependent on water pH for effectiveness. It is for these reasons that moderately hard water with a stable pH (+0.6) is preferred for use in most aquatic facilities. If the municipal water supply to a facility is soft water, careful thought should be given to various aspects of the facilities plumbing systems.

3. *Chlorine and Chloramines*

Chlorine and chloramines are added to municipal water to reduce waterborne pathogens. Unfortunately, these chemical disinfectants are toxic to species such as fish and amphibians, and must therefore be removed from aquatic facility water sources.

Although chlorine is the more potent disinfectant, the superior stability and residual effect of chloramines in solution make it the disinfectant of choice in providing potable water to major metropolitan areas. Three chloramine compounds are formed from the reaction between ammonia and aqueous chlorine; mono- (NH_2Cl), di- ($NHCl_2$) and tri-(NCl_3) chloramine. Of the three compounds, monochloramine is the most abundant disinfectant found in potable water, and is primarily responsible for chloramines' antimicrobial activity. Unlike the parent compound chlorine, which is readily removed from water with activated charcoal filtration, the extraction of chloramines from water requires a multi-step reaction and additional charcoal-bed contact time (EPA, 1999). Filtration bottles typically contain acid-washed coconut-shell carbon. A 3.6 cubic foot bottle (bed size) is about 4' tall and 14" in diameter. If the chlorine filtration system in place is working adequately, it is expected that a two-fold increase in the number of bottles will be required to completely filter chloramines from the same amount of water (M. Bercaw, US Filters, Inc., personal communication, 2005). To remove chloramines from water, first the ammonia is stripped and then the chlorine. This requires that bottles be installed in series and rows to extend bed contact time and maximize chemical adsorption (Figure 23-2). This configuration, while necessary, predisposes the water flow to partial restriction, causing a reduction in post-filter water pressure. The water flow rate through the bottles and post-bottle water pressure should be regularly evaluated. It is important to test water for chloramines and chlorine levels midway through the filtration process as well as post-filtration. If, for example, five bottles in series are used, a valve should be inserted in the water line between bottles three and four. Comparing water test results from the mid-filtration valve to those of the post-filtration water will serve as an early warning of the impending need to replace the facility bottles. Testing only the post-filtration water can lead to disaster, as chlorine and/or chloramines may already be in the facilities water system. Post-canister water should also pass through a roughening filter (Figure 23-2) to remove the charcoal particles, called *fines*, that may have been picked up as the water percolated through the carbon filter material. These filters are not 100 percent efficient, and can support microbial growth. They should therefore be changed out as part of a facility's routine preventive maintenance program. Chlorine and chloramines (or any oxidant) quickly damage most reverse-osmosis (RO) membranes and over time they will break down the resins in a de-ionization (DI) filter, allowing these disinfectants to break through the system. Therefore, it is important that chlorine and chloramines be removed from all industrial-use water entering an aquatic research facility, including water destined for RO or DI treatment. Sufficient space must be allocated for the number of filtration bottles that will be required. Bottles are heavy and awkward to move and/or transport, so consideration should be given to their location within the facility. It is important to provide easy, level access to the bottle-holding area for service and change-out purposes.

Fig. 23-2 Primary filtration system designed to remove chlorine and chloramines. In this photograph, water entering from the left is piped through five rows of activated charcoal filtration canisters (left arrow) and roughening filters (right arrow) before entering the aquatic facility.

B. Plumbing Design

1. *Water Treatment Options*

Plumbing design is pivotal to the construction of a contemporary aquatic animal research facility. Expertise in plumbing technology combined with an in-depth understanding of hydrology and aquatic science is critical. Large facilities may

necessitate the use of recirculation systems comprised of multiple pumps, water treatment devices, reservoir tanks, sumps and monitoring equipment. Mechanical, biological and charcoal filters, each having distinctly different purposes, are essential for the removal of particulates, disinfectants, contaminants and pathogens. Other water treatments commonly encountered in aquatic facilities include ultraviolet light (UV) exposure and ozone infusion. To minimize variability, many investigators choose to reconstitute *pure* water, processed through reverse osmosis (RO) or de-ionization (DI) filtration, with the appropriate minerals for their specific aquatic species. To facilitate this water preparation procedure, the inclusion of a centralized RO or DI water system with designated spigots in all aquatic animal rooms and laboratories is suggested for new facility construction. The authors suggest a centralized RO system because, compared to de-ionization, reverse osmosis consistently produces water of superior quality (Bercaw, 2005). Although RO water can be used for drinking water for non-aquatic animals, neither RO nor DI water should ever be used as aquaria water without being properly reconstituted with appropriate minerals.

2. *Domestic Supply Systems*

a. Preventive Measures for Future Concerns

The more intricate a facility's plumbing becomes, the greater the likelihood of unforeseen complications. For example, incongruent water pressure is a relatively common plumbing-related problem found in aquatic facilities. Pressure discrepancies can be found anywhere in the system, from distant facility animal rooms to between adjacent tanks. Unintended shifts in pressure can go unnoticed, but resulting problems manifest as sporadic episodes of morbidity and even mortality in affected aquaria. Diagnosis and localization of cause can sometimes be difficult. Thus, preventive measures, such as flow-monitoring devices, need to be incorporated into the system's design to ensure maintenance of adequate water pressures, levels and flow direction. Durable mixing valves coupled with high-quality cross-flow prevention should be installed, regardless of whether they are thermostatic, mechanical, automated or manual mixers. If failure occurs, thermostatic mixing valves can serve as an open connection between the hot and cold water supplies, allowing cross-flow in either direction. As a result of this cross-flow, aquaria and systems located downstream from the failed mixing valve can receive water of inappropriate temperatures, either too cold or hot. Water booster pumps and pressure-reducing valves may also be needed at various locations to ensure consistent pressures throughout the system.

b. Conduit Material

The material and dimensions of conduits are selected in relationship to various factors such as water flow rates, velocity limitations, temperatures and system pressures. Copper, nickel, cadmium, zinc (galvanized), and brass are considered taboo materials for plumbing in aquatic facilities due to the potential for heavy-metal contamination. Despite this concern copper is still used widely in plumbing systems. Under experimental conditions, copper causes acute necrosis of animal's gills at levels as low as 0.03–0.06 mg/l. Spontaneous copper toxicity in animals is nearly impossible to diagnose definitively, because of difficulties in testing and interpreting cupric water levels. While some municipal water departments add copper sulfate to water sources to help combat algae blooms, copper contaminates at the tap originate from within a facility's delivery system. Copper leaches from pipes in the form of cupric cations that are quickly chelated to organic molecules, ionically bonded to form salts, or remain as biologically active ions. The relative proportions of each vary depending on water pH, mineral content and levels of organic mass. In general, copper piping materials are safe to use if facility water remains pH neutral and hard. The chances for toxic levels of copper in water are increased in static aquaria systems where water is allowed to sit in pipes for an extended period prior to use or collection (Olsson, 1998; Grosell, 2003). Seawater is well-buffered and alkaline; therefore, it does not support toxic levels of copper or other heavy metals. Seawater is still not compatible with copper conduit, however, because it contains highly corrosive levels of salt.

The effect of copper corrosion is of significant concern to plumbing design and material selection. Conditions that contribute to water's corrosiveness include acidity, softness, salinity and water temperature. The most threatening form of corrosion, called galvanic corrosion, occurs when two electrochemically dissimilar metals, such as copper and steel, are coupled in a manner permissive of electrical flow generated by water passing through the pipes. The laws of physics dictate that when two non-compatible metals are electrolyzed in a corrosive environment, the more active metal, or anode (copper in this case), is sacrificed to corrosion at a rate faster than would occur if it were not contacting the other metal. Being more noble, the second metal (steel, for instance) becomes the cathode and corrodes more slowly than it would alone (Patil, 2003). While the steel remains minimally rusted, the copper exfoliates, forming pits and eventually perforations. Galvanic corrosion can be minimized by avoiding the direct contact of non-compatible metals, as occurs when copper conduits are suspended by steel hangers or when copper pipe is threaded into a pre-existing galvanized conduit. If copper conduit is selected as piping for an aquatic facility, consultation with an engineer with knowledge of corrosion factors is advised.

Polyvinyl chloride (PVC) is considered a suitable alternative material commonly used for aquatic plumbing. Several schedules of PVC are available, based on pressure capacities. Currently, Schedule 80 and above are preferred. Although PVC has been in use for over 35 years, its use has not been evaluated thoroughly for extended periods of time in high water-flow and water-pressure demand laboratories. Since PVC lacks the flexibility and expandability of copper, there is concern about

using it with hot water. Therefore, the installation of PVC intended to carry hot water should be given thoughtful consideration, especially if the piping will be enclosed within facility walls. It is reported that adhesives used to connect PVC piping may release acetone, methylethylketones and tetrahydrofurans for several weeks following application (Reimschuessel, 1993). To avoid this potential leaching of toxic chemicals, it is suggested that food-grade silicon sealer be used.

3. *Drainage and Discharge Systems*

Another plumbing consideration is the water drainage system that will be installed from the animal holding tanks and recirculation systems to the floor drain manifolds. It is important that tanks and systems can be completely drained of water while in place. Ideally, it should not be necessary to tip the tanks to empty them completely; this means arranging tanks and their associated drainage lines so that gravity can be used for absolute emptying.

Room trough drains located along the wall or multiple room floor drains placed throughout the room are essential. Floors should slope one-eighth of an inch per foot toward the trough or drain. The slope should be sufficient to prevent pooling or standing water, which are potential personnel slip and electrocution hazards. Since it is difficult to consistently make floors that slope to drains, the authors prefer trough drains along the periphery of the room with the entire floor sloping toward the trough (Figure 23-3). The bottom of the trough should slope one-fourth of an inch per foot toward the drain. Troughs should be covered with plastic or fiberglass grates. The grates should be cut in lengths that are easy to remove for floor, drain and grate cleaning. Locations of room floor drains must be considered well in advance. Once in place and filled with water, aquatic racks and recirculation systems are too heavy to move. The feet of the racks should not be resting on the drain grates, this prevents staff from opening and cleaning the grate, and also causes stability concerns with the rack. Drains should be flush with the floor surface and made of a rust-proof material, preferably stainless steel. Drain cleanouts should be located outside of the room if possible, and equipped with sealed access covers that are also flush with the floor surface. The drain pipes should be a minimum 4 inches (10.2 cm) in diameter (ILAR, 1996). The size and location of drains will, however, be dictated by the amount of water to be held in the room. The ability to rapidly to drain flooded water from a room will minimize water damage to the room and adjacent areas. As a room flood-control precaution, trough drains should be located along the wall opposite the door, with the floor sloping toward the trough and away from the corridor. Locating additional floor drains in the corridor outside aquatic rooms is another flood-control safeguard (Figure 23-4). Drain grates or covers should be designed to prevent animals that have become separated from their primary enclosure from disappearing down the drain. It is important to design the drain grate and possibly an inter-drain basket in such a way that animals can be quickly and easily recaptured or collected.

Fig. 23-3 Trough floor drain shown with fiberglass grate cover (end pieces removed) along the back wall of a small aquatic room. Electrical outlets are located on the wall 3–4 feet above the floor.

Discharge water containing (or with the potential to contain) life stages of detrimental species, synthesized genetic material or infectious biological agents should never be discharged into surface water. Where necessary to avoid the situation of inadvertent and possibly illegal effluent discharge, a secondary means of wastewater containment and pre-disposal filtration and disinfection should be incorporated into the facility's drainage system design. Drainage from the facility may require two separate systems. A standard sewage effluent system connected to the municipal sewage treatment plant can serve all non-laboratory areas, including shower/locker rooms and support/service area drains. All aquatic animal and associated procedure areas can be plumbed into a secondary segregated drainage system. Wastewater in the secondary sewage system drains into a containment tank, where it can be allowed to flow through or, if necessary, held and appropriately treated prior to release into the main sewage line.

4. *Noise/Vibration Abatement*

Fish have complex sensory systems, and are quite sensitive to sound (Stoskopf, 2002). The pumps, macerators and compressors used to manage large water-volume systems can be very loud and generate considerable vibration. Selecting an appropriate location for pumps is important (Figure 23-5). Large pump stations are not easily relocated once installed.

Fig. 23-4 Corridor drain and corresponding cleanout. Both the drain grate (right) and cleanout access cover (left) should be level with the floor surface.

Fig. 23-5 Pump station located outside of the building but next to an office window. Several years after installation, this pump became a source of vibrations and harsh noise in the adjacent office space.

Water pumps can even become a source of noise and vibration transmission for adjacent rooms years after installation, due to flow dynamic changes and component wear. For animal welfare as well as technician safety and comfort, ideally these pumps and generators should be housed separately from the animal rooms. The location of noise- and vibration-generating equipment in an adjacent, sound-proofed and vibration-dampened mechanical room may minimize facility disturbance. The use of anterooms, double-door entry systems, and sound-attenuating ceiling, wall and door materials should also be considered.

III. CONSTRUCTION

A. Structural Features

1. *Moisture Protection*

Facility structures, machinery and equipment must be capable of withstanding high levels of moisture. All wall, floor and ceiling treatments should be impervious to water. This includes resistance to direct spray, condensation, and high humidity. Epoxy paints provide water-resistance and are easily sanitized. Plastic-laminate systems also provide moisture protection, and may be a cost-effective selection for a facility retrofit.

2. *Flooring*

The floor surface should be evenly sloped and relatively smooth. Textured floor surfaces provide additional personnel footing safety when wet, while being relatively non-abrasive and easy to clean. The flooring material must be impact-resistant, and able to support the tremendous weight of filled aquatic housing systems without pitting or gouging of the floor surface.

3. *Walls*

Similar wall construction criteria apply for aquatic facilities as are recommended for conventional facilities. The walls should be smooth, free of cracks and uneven junctions. The surface should be moisture-resistant and capable of withstanding the force of high-pressure hosing. The facility walls should cove seamlessly into the flooring material.

4. *Ceiling*

Although ceilings might not be hosed down directly, they should be non-textured, easy to clean, and designed to withstand heavy amounts of condensation and moisture. The size and length of ceiling fixtures, such as fire sprinkler heads, light fixtures, and room ventilation and exhaust grates, must be considered during the design process. There must be adequate access clearance between these fixtures and the tops of

the aquatic racks. Unlike rodent racks, stationary aquatic racks cannot be moved easily or rolled out of the way. The location of ceiling fixtures and room placement of aquatic racks must be planned well in advance. Ceiling fixtures must also be made of moisture-resistant materials.

To maximize space, it is tempting to stack tanks as high as possible in the rooms; however, overhead clearance for the tanks must be considered. To allow access to and visualization of the animals in the tank, the minimum overhead clearance for any tank should exceed the depth of the tank itself (Stoskopf, 2002). The ability to use nets appropriately and remove tank lids should also be factored into the clearance space provided above the tanks.

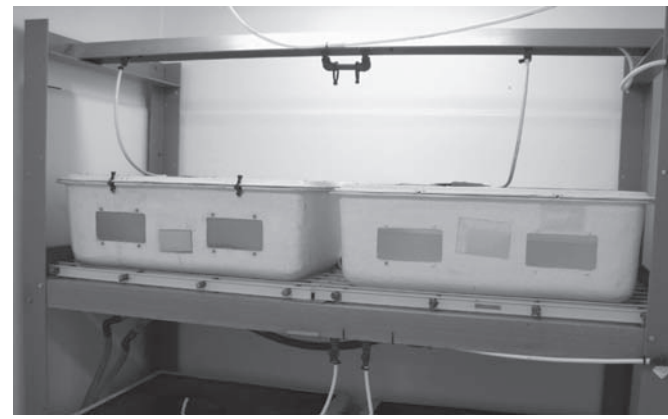
5. *Doors*

Doors and frames should be made of a moisture- and corrosion-resistant material. The recommended minimum animal room door size is 45 inches wide by 84 inches high (ILAR, 1996). The door opening should, however, be of adequate size to accommodate the racks, tanks and equipment to be used in the room. Since the doors open into the animal rooms, the size of the door and the door's swing must be subtracted from the total useable space inside the room. The door swing will also impact the selection and room location of racks and caging systems. The full swing of the room door should not be physically blocked or impeded. Doors should have a viewing panel. A tight rubber seal sweep should be fastened to the bottom of the door to minimize water leakage into the corridors and/or adjacent rooms. Due to the heavy moisture in these facilities, blind spots on metal doors, such as the bottom edge, will eventually rust and produce iron-staining on dependent structures. Thus, door and frame materials should be non-ferrous, regardless of covering treatments to be applied.

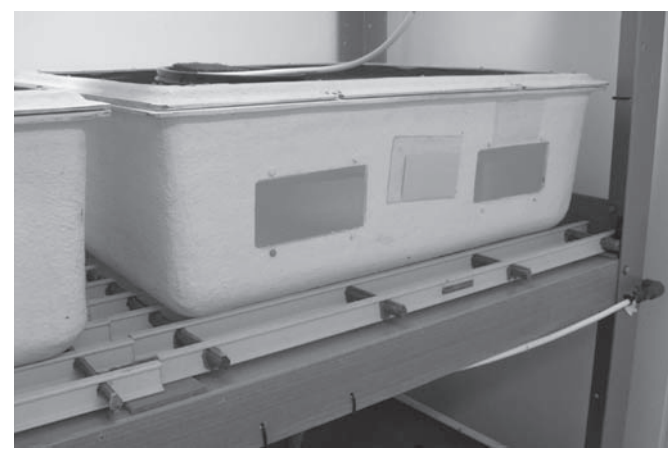
6. *Rack and Shelving Material*

The extreme weight of water cannot be over-emphasized. One gallon of water weighs over 8 pounds, and a filled 20-gallon aquarium weighs over 160 pounds. Racks, stands, shelving, carts and counters must be strong enough to support the weight they are intended to hold, and appropriately constructed to counterbalance the shifting weight of sloshing water on a sloped floor. Wall-mounted shelving must be securely braced to wall supports. In addition to the weight of the water, it is not uncommon for technicians to stand or climb on the racks to access tanks. The inappropriate design or improper use of weight-bearing structures and equipment poses a serious safety concern for both the animals and facility personnel.

Fiberglass is commonly used in facility rack construction, and is the choice of the authors. It is durable, lightweight, does not corrode, rot or rust, and has an extremely high tension loading capacity. Fiberglass racks can be built with interchangeable and variable-sized components, making them extremely flexible in design and easily configured to meet the needs of the aquaria and/or shape of the room. Fiberglass is also a relatively inexpensive material (Figure 23-6). Wooden support structures are not advised because they absorb water, warp, shrink and degrade over time. Metals that corrode should be avoided because the corrosion will reduce integrity and strength over time. Stainless steel is a variety of steel that is alloyed with at least 12 percent chromium. Commonly used AISI (American Iron and Steel Institute) stainless steel, type 316, is corrosion-resistant, but is not considered a high-strength steel. Titanium has a high strength to weight ratio. In its pure form, it is as strong as steel but about 50 percent lighter. It is used in combination with other alloys, and thus its strength will vary accordingly. Titanium is highly corrosion-resistant, and can withstand the corrosive effects of saltwater. Aluminum, which is lightweight with a high tension loading capacity, is also used for aquaria support structures. Whatever the material selection, racks and shelving should be made of laboratory-grade material and constructed by professional tradesmen who have



(a)



(b)

Fig. 23-6 Fiberglass racks offer stability, strength and flexibility, and resist water damage. Grated shelves allow for aeration and drainage. These racks are relatively easy to dismantle, and interchangeable components allow for variable rack design.

the ability to assess structural capacity. Cost will certainly be a factor in construction material selection, but material costs should not result in an inferior selection that compromises the protection and safety of personnel or animals.

B. Electrical Features

1. *Power Supply*

The most serious human safety hazard in aquatic facilities is electrocution. All electrical outlets in an aquatic facility should be GFI (ground-fault interrupted) at the circuit-breaker box. It is advisable to use ground-fault circuit breakers throughout aquatic facilities. Employees and research staff must be trained in the use of electricity in water environments.

It is preferable to avoid excessive use of electrical cords and outlet strips, but this requires thoughtful pre-planning during facility design construction. Electrical outlets should be located on walls a minimum of 3–4 feet above the floor, and additional outlets should be suspended from the ceiling (Figure 23-3). This allows easy access to the racks but keeps the electrical outlets away from hose spray and flooded water. Outlets should be sealed, made of corrosion-resistant components, and equipped with hinged, moisture-resistant covers.

2. *Light Fixtures*

Overhead light fixtures should be sealed, recessed and moisture-resistant. They should be easy to access for bulb-changing and cleaning. Fluorescent lighting is recommended. To maximize an even distribution of light to all tanks on a rack, the ceiling lights should not be arranged directly over the racks but be centered over the aisles between the racks. Lights called *wall-washers* are an additional light fixture option. These fixtures direct light onto a vertical surface, producing an even spread of light throughout an area. The light from wall-washer fixtures is reflected off the animal room walls and evenly back toward the racks.

Algae growth is dependent on light intensity, and can be a nuisance for husbandry staff. It is essential, however, to ensure that light levels are sufficient for animal health monitoring and room maintenance. There are few data regarding light-intensity levels for general aquatic species holding areas. Selecting lighting systems that provide the greatest variations to room lighting level is advisable. Providing required light to individual groups of animals per their specific requirements can best be done at the tank level. When making lighting selections there are several parameters that must be considered, including intensity, wavelength and periodicity. The bulb intensity, or amount of light delivered, is usually measured in lumens. Foot-candles or lux are units that evaluate the amount of light available at a given distance from a light source (1 lumen of light on a square meter of surface equals 1 lux; 1 lumen of light on a square foot of surface equals one foot-candle). The wavelength of light will determine its ability to pass through or penetrate certain types of water. Most marine and freshwater tropical fish can be maintained on a 12-hour day, 12-hour light–dark cycle (Stoskopf, 1993). Maintaining the appropriate species-specific photoperiod is important for the health of the animals and culture systems. Twilight timers and dimmers may also be necessary for certain species and research protocols. Room photoperiods should be controlled with automated light timers. A centralized light control monitoring panel or system is recommended. All local room switch boxes should be gasketed to the wall, made of corrosion-resistant components, and equipped with hinged, moisture-resistant covers.

3. *Emergency Power*

A fail-safe emergency power source for an aquatic facility is essential. During a power failure, the primary concerns for aquatic animal life-support are aeration, filtration/circulation, and water temperature. All critical life-support equipment must be connected to the emergency power source. Back-up generators must be properly maintained and tested regularly. The emergency power outlets in the facility should be clearly labeled. Parameter monitoring systems can be programmed to automatically dial prescribed emergency responders' telephone numbers and/or an answering service.

C. Heating, Ventilation and Air Conditioning

The heating, ventilation and air conditioning parameters for an aquatic animal facility pose unique considerations. For energy efficiency, the room air temperature is sometimes set to maintain the water temperature of the room aquaria. This may not be an optimal situation for facility personnel, and room air temperatures set greater than 26°C/80°F are generally not recommended due to the maintenance costs (Stoskopf, 2002). Setting the room air temperature at a tolerable human comfort level (21–22°C; 70–72°F) and adding supplemental heaters or chillers to individual tanks as required may be the best solution. Many modular aquatic recirculation systems have individual tank temperature control and monitoring capabilities. Heating and cooling units are available that regulate the temperature of water, and use of these units may be necessary for closed recirculation systems.

For static aquatic tanks, it is suggested that room air temperature be maintained a few degrees higher than the temperature of the tank water. This will reduce the amount of condensation accumulation in the room. Persistently high levels of condensation can damage facility structures and serve as a medium for growth of mold. Sufficient room air exchange rates will help minimize condensation, but the number of air changes per hour supplied to an aquatic animal room is an important consideration. An air exchange rate that is too rapid may

increase the rate of tank water evaporation and cause hazardous concentrations of excreted substances in the water. High air exchange rates may also cause desiccation and health problems for semi-aquatic amphibian species. The *Guide*'s (ILAR, 1996) suggestion of 10–15 air exchanges per hour for rooms holding heat-generating mammals may not be appropriate for ectothermic species. The authors suggest starting with 10 air changes per hour and then adjusting the room air exchange rates up or down, as needed per the species and the housing environment. Room air exchange rates should be checked periodically to ensure that they are holding as originally set.

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C: Special Facilities

Chapter 24

Barrier Housing for Rodents

Jack R. Hessler

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I. INTRODUCTION

In the jargon of laboratory animal science, the term *barrier* refers to animal housing systems designed and managed to protect the animals from infections with unwanted agents coming from outside the barrier. In other words, barriers are to keep out undesirable microbes. Most often the term is used to describe facilities for producing and/or maintaining rodents. The terms *barrier*, *rodent barrier* and *barrier facility* are commonly used interchangeably. The widespread use of the term barrier in laboratory animal science started in the early 1960s, primarily in reference to rodent-breeding facilities and programs designed to produce "specific pathogen-free" rats and mice for research using the trademarked name COBS™ (Caesarean Derived Barrier Sustained; Foster *et al.*, 1963). Around the same time, or soon after, the barrier concept was adopted by animal research facilities that had extensive rodent-breeding programs and for housing immunocompromised animals (Simmons *et al.*, 1967; Christie *et al.*, 1968; Brick *et al.*, 1969). As the confounding impact of infection with a growing number of agents on research outcomes became increasingly apparent, barrier housing for rodents has become standard for housing research animals in addition to breeding colonies. In the last 20 years, the development and use of transgenic and gene-targeted (knockout) mouse models rapidly increased the demand for rodent barrier housing space in biomedical research facilities to protect these unique animals. Today, most new animal facilities for biomedical research have a significant rodent barrier component, and it is common for new facilities to be entirely dedicated to housing rodents under barrier conditions.

Barriers may consist of single or multiple layers of protection, with both physical and management components. Use of multiple layers reduces risks; however, where people are involved, there is no such thing as a totally protected, risk-free facility.

The physical component can be a cage, an isolator cabinet, an animal room, an area of a facility, the entire animal facility, or any combination thereof serving as primary, secondary and tertiary barriers. The management component involves operational procedures designed to prevent the introduction of undesirable infectious agents into the barrier. The most important factor for preventing entry of unwanted agents is a well-trained animal-care and research staff. The staff must be aware of the hazards and be proficient in techniques to control contamination of the facility and the animals. The staff must be responsible for strictly following barrier practices with special equipment, facility features and management practices.

The most common rodent barrier in use today is a cage-level barrier system referred to in this chapter as the *micro-isolation caging system* (see Chapter 20 in this book). This "system" combines the physical attributes of a micro-isolation cage and a biosafety cabinet (or similar HEPA filtered air cabinet/"cage-change station") with management procedures. Everything that the animals contact is to be sterilized: the cage, bedding, water and feed. The system is completed by opening the micro-isolation cage only inside the HEPA filtered air environment of a biosafety cabinet. Regardless of the barrier system used – a cage-level barrier, a facility-level barrier or a combination of both – the facility design greatly impacts the efficiency with which barrier housing can be provided.

A common component of all barriers is equipment for sterilizing cages and supplies that have direct contact with the animals. Typically this involves an autoclave, although other types of sterilization equipment are available. Because autoclaves are the most commonly used sterilization equipment for barriers, the focus in this chapter will be on autoclaves; however, the same general features apply to other types of sterilization equipment (see Chapter 31 in this book).

II. BARRIER HOUSING IN CONVENTIONAL ANIMAL ROOMS

The most basic approach to providing barrier housing for rodents is to use a conventional animal room. The room ventilation may be balanced positive to the corridor as a secondary barrier, with various types of cages and equipment serving as the primary barrier (micro-isolation caging system and various types of isolator cabinets or flexible film isolators of the type used for maintaining germ-free animals). When properly used, this approach is effective. Most conventional animal facilities are able to set up this type of rodent barrier housing program with minimal start-up expenditure, other than the cost of additional autoclaves.

This approach offers the greatest flexibility for use of the animal housing space. The primary disadvantage is that it is labor-intensive, making daily animal maintenance costs higher than inside a dedicated barrier. The primary reason for the relatively high labor cost with the cage-/room-level barrier system is that the cages and supplies are wrapped and autoclaved elsewhere in the facility before being transported to the animal rooms, where they are unwrapped. This approach is reasonable so long as the numbers of cages are small, but becomes unwieldy as the number of cages increases. In dedicated barrier space the cages and supplies are autoclaved into the barrier through a double-door pass-through autoclave and once inside the barrier they are handled in a conventional manner, eliminating the need for wrapping and unwrapping the cages. Some facilities just cover the sterilized cages with drapes while transporting them, which reduces the labor of wrapping them like a surgical pack. The risk of contamination with the wrap or drape method is that the cage covering may be contaminated after autoclaving and in the process of rolling cage carts and racks through the facility corridors before entering the animal room. In facilities with effective programs to keep undesirable infectious agents out of the animal facility, this risk may be considered acceptable.

III. DEDICATED BARRIER FACILITY

The objective of a dedicated rodent barrier facility is *effectively* and *efficiently* to maintain the animals free of specific infectious agents. As noted above, the most commonly used primary "barrier" is the micro-isolation cage system. It, in combination with a dedicated animal room, is capable of satisfactorily achieving the "effectively" part of the above-stated objective. A "dedicated barrier facility," which is created by establishing a perimeter to control the entry of animals, people, equipment and supplies, certainly enhances the "effectively" part of the objective, but its primary contribution is to facilitate the "efficiently" part of the objective. A properly designed and managed barrier facility makes it possible to maintain rodents free of specific infectious agents at little more operations cost than the same species maintained in conventional facilities.

A barrier may be a circumscribed area within the animal facility, a floor of a multi-level animal facility, or may be the entire animal facility. Figure 24-1 is a plan of a barrier that occupies the entire floor of a multi-floor animal facility. The entire animal facility illustrated in Figure 24-2 is a barrier facility. Facility features are important aspects of a barrier; however, the cage-level barrier remains the most important barrier in a barrier facility.

The following are critical parts of any plan designed to facilitate maximizing both the "effectively" and the "efficiently" components of the objectives for barrier facilities that are stated above:

- an operational plan, which must be formulated during the programming stage, that minimizes the number of times that cages are handled outside of the cage-wash area (it is

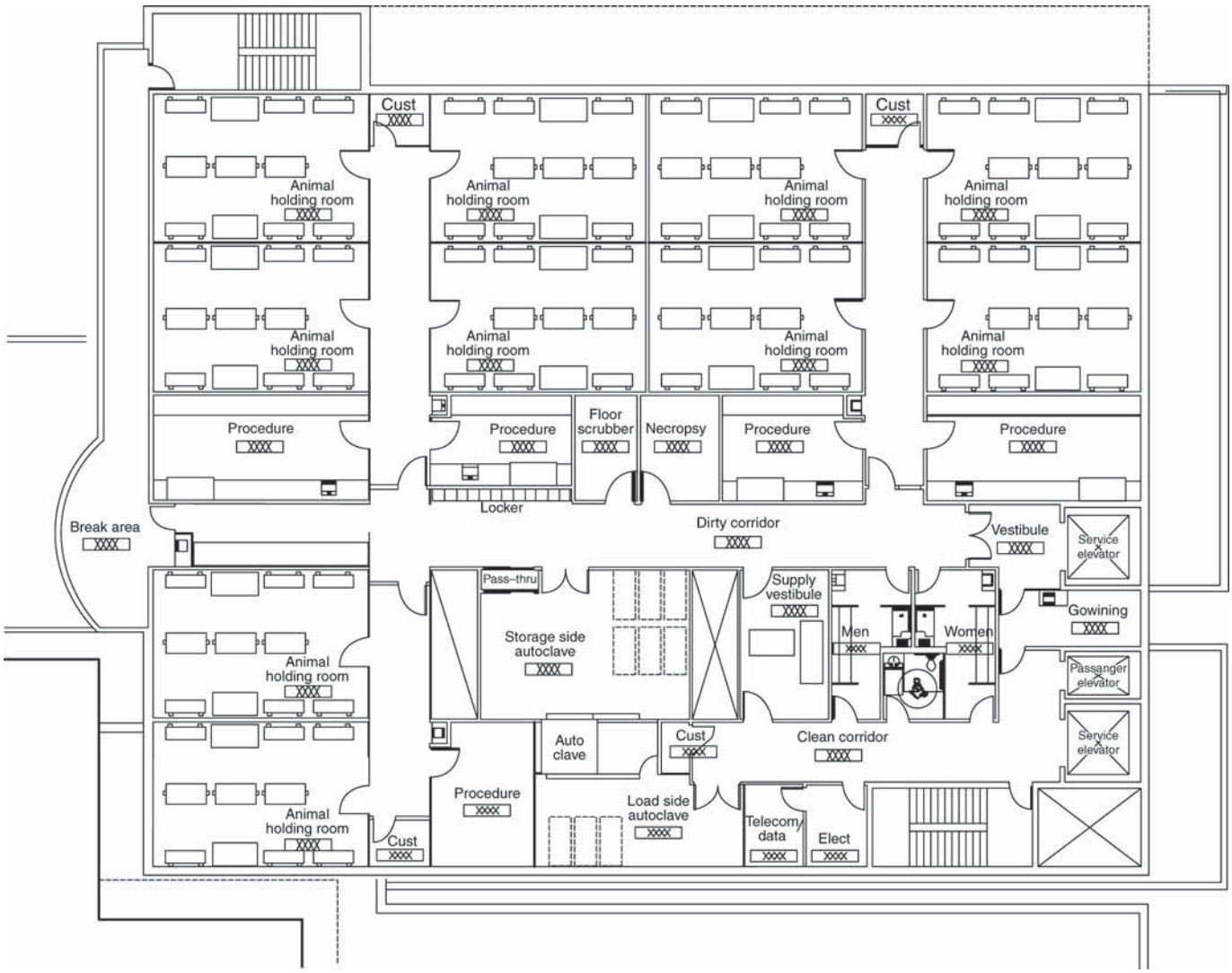

Fig. 24-1 Schematic of an 8,400-mouse-cage capacity barrier facility that occupies the entire floor (15,000 gross sq. ft, 13,000 net sq. ft.) of a multi-floor animal facility.

This is a single-corridor design with side suites off a main corridor with animal and procedure rooms. All vertical circulation space (elevators and stairwells) is located outside of the barrier. The elevators are located at the bottom right corner of the schematic. The cage-wash area is on another floor. The cages are transported to the barrier floor on a "clean" elevator. Once on the floor, they are passed into the barrier through a floor-loading bulk autoclave. Inside the barrier is storage space for the sterilized cages. Soiled cages are transported out of the barrier through a vestibule into the "dirty" elevator to the cage-wash area. Personnel enter through locker rooms, and supplies enter through a vestibule. Inside the barrier are five procedure laboratories and a necropsy room, a break area, and three small custodial closets plus a storage room for custodial supplies and equipment. Other animal-use space, including a transgenic laboratory, is available in other rodent barriers located on other floors of the facility.

the author's opinion that the most efficient plan includes handling all cages, from the time the clean cages are taken out of the cage-wash area to the time the soiled cages are returned to the cage-wash area, as completely set-up cages with bedding, wire lids and filtered tops in place);

- an appropriately sized floor-loading hi-vacuum autoclave as an integral part of the perimeter that forms the barrier;
- an efficient way to transport cages; and
- a well-planned facility layout that facilitates the routine logistics of animal care.

Barrier facilities are designed and managed at various levels of microbiological control, which translates to mean the degree of control over how everyone and everything enters the facility. Some animal facilities may have more than one barrier, and each may be operated at a different level. There are many operational factors that establish the barrier level. Entry requirements for personnel are just one example. A high-level barrier for maintaining the breeding stock of valuable transgenic/KO animals may limit access to a few people, and have shower and clothes-changing entry requirements. A lower-level barrier used for housing animals on study may approve

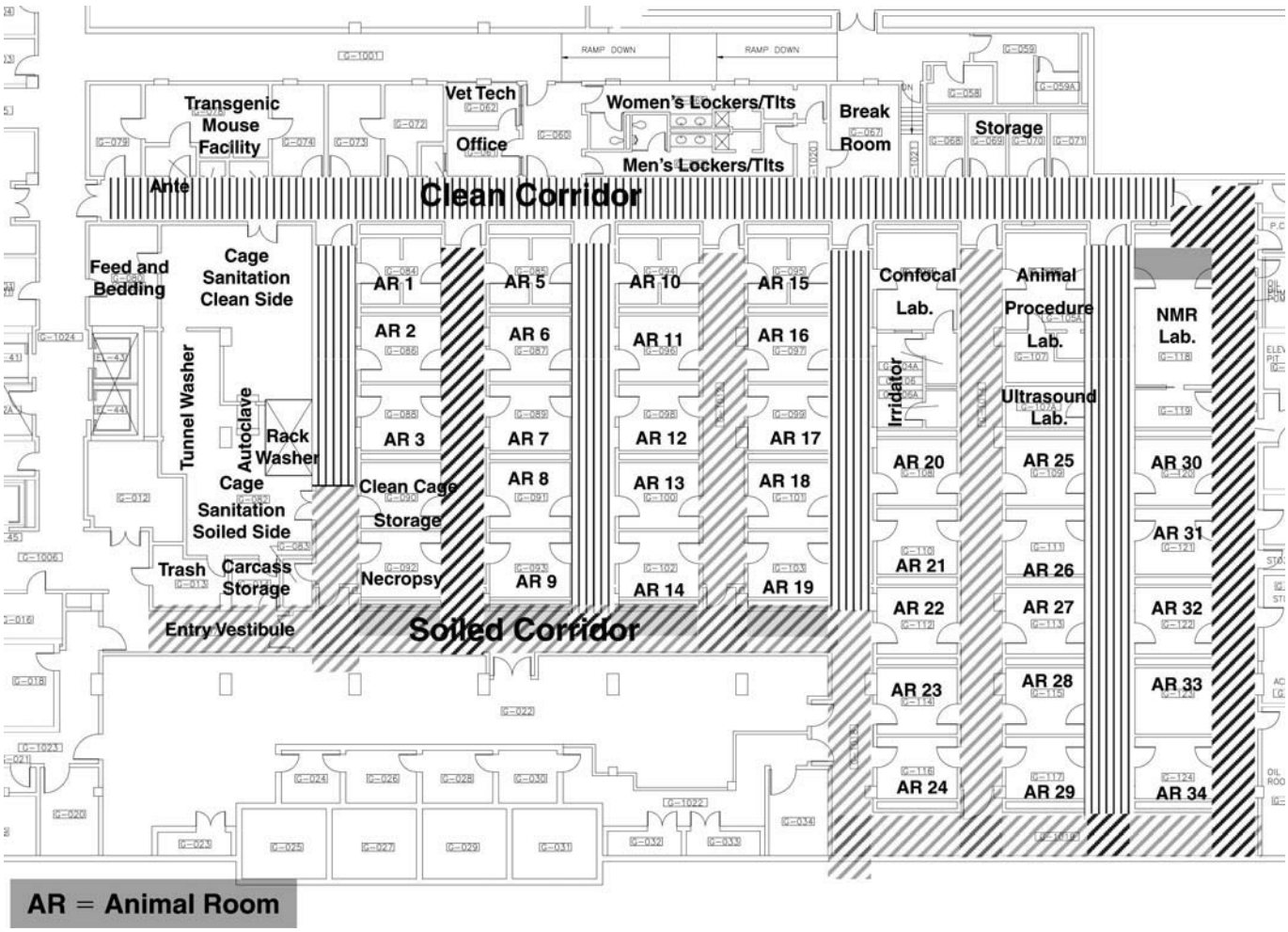

Fig. 24-2 Schematic of a self-contained 17,750 net sq. ft. 10,000-mouse-cage capacity rodent barrier facility complete with a cage-wash area inside the barrier.

This is a dual-corridor design with secondary crossover corridors connecting to primary clean and dirty corridors. There are 29 × 154-sq. ft. animal rooms, each with three ventilated cage racks, plus four cubicle rooms, each with four cubicles. The small size of the animal rooms combined with dual corridors results in an inefficient design, with corridors occupying 39 percent of the net square footage. Just 21 percent of the 10,750 net assignable square feet (not including 7,000 sq. ft of corridors) in the facility is animal procedure space, including a transgenic laboratory, an MRI laboratory, an ultrasound imaging laboratory, a confocal microscope laboratory, two general animal procedure laboratories and a necropsy room.

access for many persons, and entry requirements may include only a limited amount of personal protective equipment (PPE) over street clothes. The facilities for the two could be identical, with the exception that the first would require dressing rooms and showers instead of a gowning/de-gowning vestibule.

A. Barrier Entry/Exit Ports

Regardless of the management level chosen, the need for entry and exit ports that form the boundary between inside and outside of the barrier will be similar. Considering all that must enter and exit the barrier on a routine basis, including animals, people, caging equipment, feed, bedding, other supplies, soiled cages and trash, this is a major challenge. The design and management of a barrier must focus on facilitating management's ability to meet this challenge.

1. *Access and Egress for Cages, Other Equipment, Water Bottles, and Supplies*

a. Access via Sterilizer

All equipment and supplies that can be autoclaved will enter the barrier through double-door pass-through autoclaves. Because cages make up such a large percentage of the volume to be processed into the barrier, the primary focus in planning a barrier will be on processing cages into the barrier.

To Nest Cage Parts or Stack Fully Assembled Cages? As noted above, it is the author's preference to autoclave cages completely set up and ready to use with cage bottom, bedding, feed (optional), wire lid and filter top, *sans* water bottles, in order to achieve maximum operational efficiency. Assembled cages require significantly more autoclave capacity and transport capacity than nested unassembled cage parts, but assembling cages is much more efficiently done in the cage-wash area than in the animal room. In addition, this eliminates opportunities for cross-contamination when the cages, after being autoclaved, are only opened inside a cage-change cabinet and when both the clean and soiled cages are being transported with the filter tops in place.

Autoclave cage capacity can be greatly increased if the cage parts are stacked nested while being autoclaved and assembled later; however, this requires handling individual cages before they can be used, which negates some of the efficiency that justifies the dedicated barrier facility. An alternative strategy is to autoclave the cage parts stacked nested, and then set them up into completely assembled ready-to-use cages in dedicated space inside the barrier before delivering them to the animal rooms. This is still more efficient and safer, in terms of opportunity for cross-contamination, than setting up the cages in the animal room, and the additional labor is partially offset by reduced labor costs in the cage-wash area.

Autoclave Capacity The autoclave capacity must be carefully sized to handle the calculated weekly autoclave load, based on the cage capacity of the barrier multiplied by the number of changes per week. This calculation is made as part of the programming process. If ventilated cages are to be used, the number of cage changes may vary from 0.5 to 1 time per week; if static cages are to be used, up to 2 times per week. Other factors in the equations include the number of autoclave cycles that can be completed in a typical work day (e.g., 6) and the number of autoclave cycles that will be required for cage racks and other equipment and supplies. A reasonable starting assumption may be that two-thirds of the autoclave cycles will be devoted to cages and cage racks, and one-third to other equipment and supplies. Many factors affect this ratio, including whether automatic watering or water bottles will be used, and when water bottles are to be filled – before or after autoclaving (see the "Water bottles" and "Autoclave throughput calculation" sections below).

Water Bottles If water bottles are to be used, they will be transported in wire baskets with separate compartments for each bottle – typically 24 bottles per basket. The baskets are transported on bottle-basket dollies specially designed for the wire baskets. A typical bottle-basket dolly measures $20'' \times 26''$, and will hold six baskets when stacked three baskets high. Empty bottles can be autoclaved in the same cycles with other equipment, including cages. If water bottles are to be autoclaved full of water they will be autoclaved separately, since the cool-down phase of a liquid autoclave cycle is very long. Autoclaving a liquid load at the end of the day helps with scheduling. Alternatively, empty bottles can be autoclaved into the barrier and filled inside with acidified RO water, which is certainly clean enough for use inside a barrier. Water bottles will be added to the cages inside the cage-change cabinet at the time the cages are changed, and between changes as required. It should be remembered that water bottles may require changing at least once a week even if the cages are only changed once every 2 weeks.

Autoclave Contingency Plan Programming should include a contingency plan for when an autoclave is out of service, since the daily operation of the barrier is totally reliant on the autoclave. Unless two autoclaves are installed with each providing 100 percent of required capacity, the contingency plan will involve some degree of operational compromises. Alternative options to having two fully redundant autoclaves include the following:

1. Installing two autoclaves, each having a minimum of 50 percent of required capacity, and lengthen the cage-change cycles until full autoclave capacity is restored. **Caution**: Since pricing of bulk autoclaves is not linear with the chamber size, the cost of two autoclaves with 50 percent capacity is significantly more than one with 100 percent capacity, and may not be much less than two with 100 percent capacity.
2. Relying on other autoclaves in the facility, so long as they have the required capacity, and transporting sterilized items to the barrier. Doing this after regular hours avoids compromising operations in the area being served by that autoclave.
3. Going with one autoclave, maintaining a supply of spare parts on hand and hoping that the autoclave can be promptly returned to service. An inventory of autoclaved cages and supplies can be buildup inside the barrier if it is known that the autoclave is going to be down for routine maintenance.

Cage Transport Carts As noted above, the cage transport system is a critical component of the "efficiently" objective. It should be designed to transport fully assembled cages throughout their entire trip, from where they are loaded and stored on the clean side of the cage-wash area, through the facility corridors to the barrier autoclave, to the animal room, and then to the soiled side of the cage-wash area to be unloaded for washing. During this entire trip, the only time a cage is handled is when a soiled cage is being exchanged for a clean cage in the animal room. The transport carts should be small enough so that two can be used in the animal room during cage-changing – one with the fully assembled clean cages and one on which to stack the assembled soiled cages – and large enough to hold a significant number of cages. For example, a cart measuring

26″ deep × 36″ wide will hold up to 80 fully assembled (cages, bedding, feed, wire lids and filter tops in place) micro-isolation mouse cages (4 cages wide × 2 deep × 10 high – or even higher with low-profile micro-isolation cages). The cage transport cart that has just been emptied of its clean cages becomes the next recipient of soiled cages.

An alternative to transport carts is always to transport the cages on the cage racks and change the racks each time the cages are changed. This is a viable option; however, given the size and weight of the full racks combined with the fact that it is not necessary to change the racks that often, since the animals have no contact with them, the pros and cons of this option should be carefully weighed.

Autoclave Throughput Calculation The following is an example of an autoclave throughput capacity calculation:

> A floor-loading high-vacuum autoclave with chamber sizes 84″ high × 84″ long × 64″ wide will hold 2 double-sided ventilated mouse racks each measuring 30″ wide × 72″ long and holding 140 cages (a total of 280 cages fully assembled cages) or 4 cage transport carts each measuring 26″deep × 36″ and holding 80 cages (a total of 320 fully assembled cages). Assuming an average of 300 cages per load (the actual average will depend on the frequency of rack changes) and 6 loads per day, the throughput capacity of cages in one day would be 1,800 cages. Assuming that 20 of the 30 potential weekly loads are used for sterilizing cages, then this one autoclave would have the capacity for autoclaving 6,000 cages a week. If cages are changed weekly, this would be adequate for a 6,700-cage barrier (assuming 90 percent is the maximum operational capacity).

Of course, if cages are changed bi-weekly, it would have the capacity to autoclave fully assembled cages for a 13,400-cage barrier. The capacity could also be increased by increasing the number of loads per day, either by extending the number of hours the autoclave is in service each day or by shortening the autoclave cycle (some use a shorter "pasteurization" cycle for cages to increase output and decrease cage damage); by decreasing the frequency of rack changes; by stacking the cages higher on the transport carts; by increasing the number of cycles available for cages by using automatic watering, etc.

The same autoclave could hold nine 20″ × 26″ bottle-basket dollies, each with 144 bottles for a total of 1,296 water bottles per autoclave cycle. Therefore, 5 autoclave cycles would be required to provide bottles for the same 6,700-cage barrier facility noted above.

b. Entry Vestibule for Items That Cannot Be Autoclaved

Such items can be introduced through a vestibule or fumigation chamber. Most barrier facilities would not have a fumigation chamber such as would be used in a high-level biocontainment facility (see Chapter 25 in this book), but it may be worth considering. A dedicated, well-ventilated entry vestibule with interlocking doors where the surface of the equipment or supplies can be sprayed with a chemical disinfectant is required. This vestibule should be separate from a vestibule used by personnel to enter and exit the facility because of the disinfectant chemical routinely used in the vestibule. Sometimes a pass-through dip tank filled with high-level disinfectants may be made available to pass sterile items packaged in watertight containers into the barrier.

c. Exit Vestibule for Soiled Cage, Trash and Animal Carcasses

As a general rule, a separate exit vestibule is required for soiled cages, trash, and animal carcasses. Ideally, it should exit the barrier at a location convenient to the soiled side of cage-wash or an elevator leading to the soiled side cage-wash. It should be large enough to hold a significant number of soiled cages and trash containers, because the items will be placed in the vestibule by technicians working inside the barrier and removed by technicians working outside the barrier. In a very small barrier, space considerations may dictate using the same entry vestibule as that used for items that cannot be autoclaved (see above).

2. *Access and Egress for People*

Requirements for people entering a barrier vary considerably depending on the function of the barrier, the primary activity of the individual inside the barrier, and the management philosophy. Rodent production barriers often require a shower and change of clothes to enter. Animal-care staffs in research facilities are always required to change into a work uniform, but may or may not be required to change again to work inside a barrier. If they don't change, they may be required to don PPE over their work uniform. Research staff members entering a research barrier facility are typically required to don PPE over their street clothes.

a. Gowning/Un-Gowning Vestibule/Room

This is the most common entry path in most research barrier faculties. In it, people don PPE over their street clothes or work uniforms before entering the barrier and remove them when exiting the barrier. Depending on the anticipated traffic, it could be a 10′–20′ section of a 7′- to 8′-wide corridor created with interlocking doors, or a separate room with two doors, one connecting the room to outside the barrier and the other to inside the barrier. At a minimum it requires mobile shelves for holding the PPE and trash container for used PPE. A nearby storage room for PPE is highly desirable. A bench where people can sit to don shoe covers and wall hooks for hanging coats is also desirable. Sometimes there is a line in the floor separating the "outside" portion of the floor from the "inside" portion. As people don shoe covers, they step over the line toward the barrier, taking care not to allow the shoe cover to touch the "outside" portion of the floor. The availability of benches on both sides of the line facilitates this otherwise acrobatic exercise. Another option is to have a bench separating "inside" and

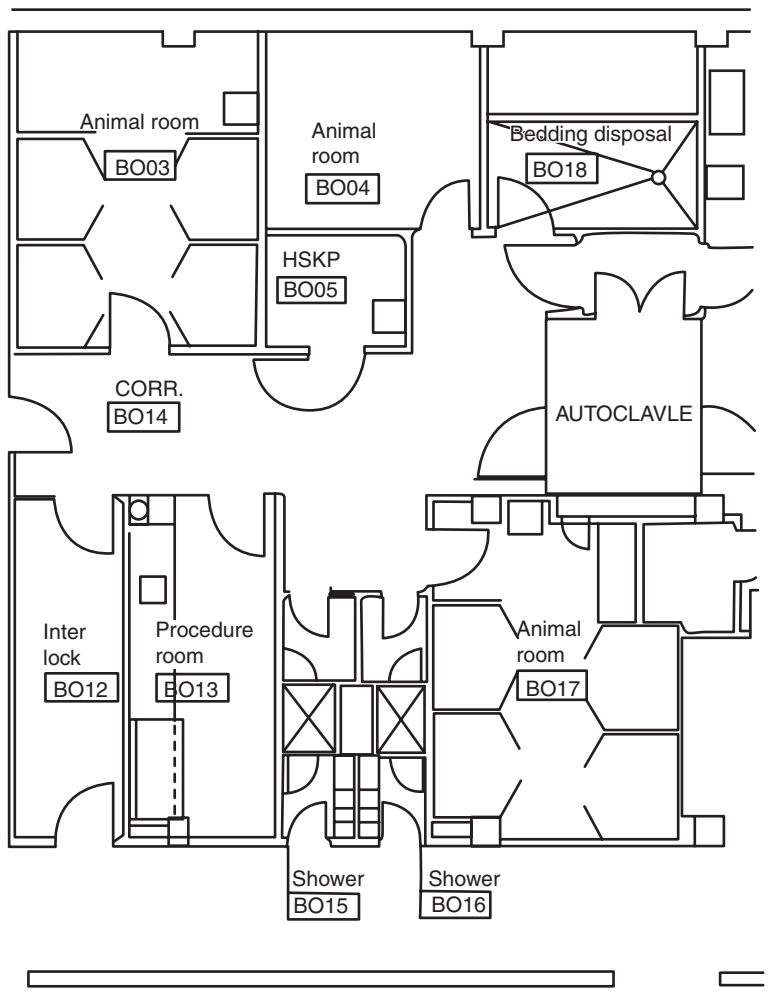

Fig. 24-3 (a) Schematic of a small containment facility provided to illustrate the 4′6″ × 14′0″ private unisex dressing/shower rooms at the lower center of the schematic (labeled "shower") that are suitable for barrier or containment facilities. Each dressing/shower room consists of three compartments; a dressing room with lockers for street clothes, a shower, and a dressing room where a work uniform is donned prior to entering the containment or barrier area. In a barrier facility, people would shower in; in a biocontainment facility, people would shower out and may also shower in.

"outside," using a "bench over" technique. Personnel sit on the bench facing outside, don a shoe cover and rotate, placing this foot inside. They then don the other shoe cover and place the second foot on the inside.

b. Air Shower

Air showers blowing mass quantities of HEPA filtered air onto those passing through after donning PPE may be added to a personnel entry vestibule. However, the efficacy and/or cost-effectiveness of air showers is still in question.

c. Shower/Change Room

Some barriers may require a wet shower and change of clothes to enter. Typically the traffic flow would be from the entry side, where street clothes are placed in a locker, through a shower into the barrier side, where work uniforms are donned prior to entering the barrier. Egress from the barrier should lead either to the entry side of the locker room or to outside the barrier, from where people can return to the entry side of the locker to retrieve their street clothes. Alternatively, people could egress back through the shower, without showering out. This can all be accomplished in an area as small as 4.5′ × 14″ (see Figures 24-3a–c). One or a series of two or more of these private gender-neutral locker/shower rooms, depending on the anticipated traffic, can efficiently satisfy the need for showers/locker rooms, and are well received by personnel. Electronic door locks with switches at both doors that simultaneously lock and unlock both doors assure privacy. One or more larger locker/shower room(s) may be needed to provide disabled access.

Fig. 24-3 (Continued) (b) Photograph of such a dressing/shower room looking into the entry portion with lockers. Note the closed shower door. (c) The same view as (b) with the shower doors open, looking through to the door leading into the containment area.

3. *Animal Access and Egress*

Rodents are typically delivered to the barrier in filtered shipping containers. Ideally, the exterior of the boxes will have been sprayed with a high-level disinfectant at the receiving area of the facility and then again at an entry vestibule (which may be the same entry vestibule for items that cannot be autoclaved described above) before being taken to the animal room, where the animals are transferred into cages inside the biosafety cabinet. In barrier facilities that receive a large number of animals from the outside, a dedicated animal receiving room is highly desirable. Half of the receiving room would be outside the barrier, the other half inside the barrier. In between is a pass-through biosafety cabinet in which animals are transferred from the shipping container to cages. Egress for both live and dead animals would be through the same exit vestibule used for soiled cages.

B. Animal Housing Space

Most of the animal housing space will consist of standard animal rooms (see Chapters 4, 18 and 20 in this book). Most barriers will require some quarantine rooms with animal cubicles (see Chapters 15 and 26 in this book) even if a microisolation caging system is to be used.

C. Animal Care and Facility Support Space

1. *Cage Sanitation Space – Inside or Outside of the Barrier?*

In a facility where the barrier is only a portion of it, the obvious location for the cage-wash area is outside of the barrier. Where to place the cage-wash area in a facility in which all the animal housing space is behind a barrier deserves careful consideration. The cage-wash area for the barrier schematic in Figure 24-1 is outside the barrier on a different floor of the animal facility. The cage-wash area for the barrier schematic in Figure 24-2 is inside the barrier.

Theoretically, if the cage-wash area were inside the barrier, it would not be necessary to autoclave the cages because the180°F (88.2°C) water used in the cage-washers kills most of the microbes of concern. Assuming that the cage washers consistently maintain high enough temperatures to effectively kill the agents of concern, then cage-washing combined with

using irradiated feed and bedding should essentially be the equivalent of autoclaving. This seems to be sound logic and, in a breeding barrier facility with very limited access and rare introduction of new animals, may be a reasonable approach.

However, in a research environment with multiple users and frequent additions of new animals from multiple sources, the odds are that there will be disease outbreaks inside the barrier. For this reason, research barrier facilities need to be managed in part as though they are a biohazard containment facility, with the objective being to contain infectious agents that get into the barrier until they can be detected and eliminated from the barrier. Based on this line of thought, the question of where to place the cage-wash area – inside or outside the barrier – can be answered by answering the following questions:

1. Where would be the best location to dump soiled bedding from a cage that is contaminated with mouse hepatitis virus (MHV): inside or outside the barrier?
2. If you know you are dealing with a MHV outbreak in a barrier facility, which would you rather rely on to provide assurance that you are not spreading it throughout the facility with recycled contaminated cages: a cage-washer or an autoclave?

To this author, who has personal experience with this exact situation, the answer to both questions is obvious; the cage-wash area must be outside the barrier and the cages should be autoclaved back into the barrier. Others may have a different answer.

2. *Autoclave Staging Space*

Outside the barrier, at the entry door to the barrier autoclave, there needs to be a staging area where the next autoclave load can be stored in anticipation of being loaded into the autoclave for the next cycle.

3. *Storage Space for Sterilized Cage and Water Bottles*

Cages coming out of the autoclave are hot, and need time to cool down before they are used. In addition, the autoclave output may not correspond precisely with the demand for clean cages throughout the day. Ideally, there should be storage space for a 1-day supply of sterilized cages. If nested cage parts are autoclaved instead of set-up cages, room should be planned in this space for assembling and setting up the cages and filling them with feed (the bedding can be in the nested cage bottoms). A separate storage space convenient to investigators is desirable for storing set-up cages required by investigators to house weanlings or separate out animals for other reasons.

If water bottles are to be filled inside the barrier, a place for water-bottle filling equipment and for storage will also be required.

4. *Supply and Feed Storage Space*

Storage space will be required for PPE and for sanitation and other miscellaneous supplies. In addition, feed storage space will be required inside the barrier. The amount needed will depend on how it is handled. Options include putting it in the feeders of the set-up cages and autoclaving it with the cages. In this case, a minimal amount of feed will be required inside the barrier for topping off feeders between cage changes. If it is necessary to assemble cages after autoclaving a significant amount of feed storage space will be required, since all of the feed used in the barrier will be added to the cages inside the barrier at the time the cages are assembled. In this case, it is important that feed storage be located immediately adjacent to where the cages will be assembled and set up for use. Either the feed will be introduced into the barrier through the autoclave, or irradiated feed will be introduced through the entry vestibule for items that cannot be autoclaved described above. Inside the vestibule, the outsides of the feed bags will be sprayed with a high-level disinfectant. Equipment similar to a mini tunnel washer is available to facilitate spraying down all surfaces of the bags. Planning should include making sure that the vestibule will accommodate such equipment if it is to be part of the program.

5. *Personnel Accommodations*

Depending on the size of the barrier, this type of space may vary from non-existent, to a single small room, to a significant amount of space. The barrier may be the primary work environment for the animal technicians caring for the animals in the barrier, as well as for some of the research technicians. Depending on the entry requirements, entering and exiting the facility for biological and rest breaks may not be practical or cost-effective. In addition, there needs to be good electronic communicator between the inside and outside of the barrier. There may also be a need for a supervisor's office inside the barrier. Management philosophies regarding these issues will vary, but spaces to be considered include an office for the facility supervisor, a room for electronic monitoring and IT communications equipment, a lavatory or lavatories, a break area, shower/locker rooms as covered above, etc. To keep the amount of electronic equipment and computers entering the barrier to a minimum, computers with either wireless or hard-wired links to the outside should be made available within the barrier.

Given the amount of time and effort some staff will spend in the barrier, esthetics of the work environment should have a high priority (see Chapter 11 in this book).

6. *Janitorial Service Closets*

Strategically located janitorial service closets will be required throughout the barrier to facilitate caring for all the

rooms and corridors in the barrier. The number will depend on the size of the barrier. If there are extensive corridors, a room with appropriate power and plumbing features will be required for storing and maintaining walk-behind, battery-powered floor-care equipment.

D. Animal-Use Support Space

Most rodent barrier facilities have standard operating procedures that preclude returning animals to the barrier once they have been removed. This means that most barriers supporting research will require a significant amount of space devoted to animal use. The amount and types of spaces will vary with each facility. The barrier facility illustrated in Figure 24-2 has 21 percent of the net assignable square footage as animal-use support space (see Chapter 19 in this book for a detailed description of the various animal-use spaces). Following is a brief listing and explanation of the needs for some types of animal-use spaces that may be required inside a rodent barrier facility.

1. *General Animal Procedure Space*

Most routine animal procedures, such as weighing, dosing, collecting body fluids, etc., are performed in the cage-change cabinet in the animal room. For this reason, the number of these cabinets in an animal room per number of cages is a critical factor. As a general rule, there should be at least one cage-change cabinet per every three double-sided racks of cages, which may include 140 or more cages per rack. The process of changing this many cages weekly will tie up one cage-change cabinet for approximately 1.5 days, during which time investigators will not have access to the cabinet to perform procedures with their animals. For a variety of reasons, it may not be practical or even possible to perform the procedures in the animal room. In those instances, general animal procedure rooms are required. It is difficult to estimate how many will be required, but a starting point for discussion during the planning phase may be one for every five rooms. Procedures will often be performed in biosafety-type cabinets of larger sizes than those in animal rooms. For certain types of studies, such as behavioral studies, each animal room may require having an adjacent procedure room. Each procedure room must have the same architectural and engineering features as an animal room, and should be outfitted with casework, etc., that facilitates easy conversion to an animal room.

2. *Storage Space for Investigator Supplies*

Investigators will require a significant quantity of routine laboratory supplies, such as needles, syringes, test tubes, tissues, drapes, etc. Given the requirement for introducing supplies into the facility, it is not practical for investigators to bring in the supplies required for each day on that day; therefore, secure supply storage cabinets should be available for assignment to investigators as they require them. Each cabinet should have locks that provide secure space for each individual but that also provide universal access for the management of the facility. A good location for these cabinets is in recessed areas of the corridor, scattered conveniently to as many animal rooms as possible. Procedure rooms provide another possible location, but have the disadvantage of possible conflicts when the room is in use.

3. *Necropsy*

This is a specialized animal procedure room used exclusively for euthanizing animals and collecting specimens *post mortem*. It may have a rodent-size down-draft/back-draft necropsy table with an overhead examination light, a back-draft formalin tissue-trimming table, some casework (including over and under cabinets and drawers), one or more CO_2 euthanasia chambers supplied by piped in CO_2, and room for a refrigerator and freezer for storing animal carcasses.

4. *Transgenic/KO Laboratory*

This is where transgenic and knockout mice are made. It is also where animals may be re-derived by embryo transfer. Not every barrier will require having a transgenic/KO laboratory, but when an institution does require one it is typically located inside a barrier. Ideally, it will have access and egress both from inside and outside the barrier.

5. *Surgery Laboratories*

Most routine surgical procedures performed on rodents can be carried out in the biosafety or cage-change cabinets in the animal or procedure rooms; however, where it can be anticipated that a large number of surgical procedures will be routinely performed, a room dedicated to performing surgery on rodents can be best arranged and equipped to facilitate the surgeries.

6. *Specialized Laboratory Spaces*

The number and type of specialized laboratories required inside the barrier will vary considerably. The two most common are various types of imaging laboratories, and a room equipped with an irradiator. Also common are behavioral laboratories. Ideally, some of these laboratories, especially the imaging laboratories, should also have access and egress both from inside and outside the barrier. That way, animals from outside the barrier can be taken into them without being brought through the barrier.

IV. SUMMARY

Barrier housing for rodents to protect them from becoming infected with pathogens and adventitious agents has long been a standard for rodent production facilities, and more recently has become a standard for animal research facilities. The primary decision to be made when planning a research facility that will house rodents is whether to provide the barrier housing using a micro-isolation caging system inside a conventional animal room, or to create a physical barrier in a dedicated area of the facility. Both approaches effectively protect the animals, with the dedicated barrier facility arguably offering a higher level of protection. The room-level barrier has the advantage of allowing maximum flexibility for use of the animal housing space. The dedicated barrier has the advantage of being less labor-intensive, lowering the daily maintenance cost. Information is provided to help make this very important programming decision, along with suggestions and information regarding rodent barrier design features.

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Chapter 25

Biohazards: Safety Practices, Operations and Containment Facilities

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I. INTRODUCTION

The focus of this chapter is the containment of biohazardous agents in work with animals. Much of the discussion on biohazards also applies to the containment of radioactive and chemical hazards used with animals.

A. Safety Objectives

Safety in the animal laboratory involves work practices, special equipment and facility features that help manage and reduce risks when working with hazardous agents in animals. The intention is to hold hazardous agents within fixed limits,

as close to their source as possible, to minimize or eliminate the inadvertent exposure of persons, animals and the environment, and to safeguard the veracity and quality of the research.

B. Elements of Safety

Safety in the animal laboratory is achieved and maintained by three basic elements:

1. Standard research/animal husbandry practices and techniques
2. Special safety equipment (primary containment)
3. Facility design and engineering features (secondary containment).

C. Laws, Regulations, Standards and Guidelines

Although there are animal welfare laws that apply to laboratory animals, these laws do not relate specifically to animals with infectious diseases. The laws that are of particular concern in containment facilities relate to possession and use of specific infectious agents (DHHS/CDC, 1996; DHHS, 2005; USDA, 2005). These laws regulate containment practices and security for facilities handling infectious agents, including animals infected with the agents.

In addition to the select agent regulations, design and operational requirements may come from institutional guidance and from other guidelines related to biosafety. Guidelines may be voluntary or required due to facility funding sources. Guidelines for the use of infected animals include the following:

- *Biosafety in Microbiological and Biomedical Laboratories* (Richmond and McKinney, 1999), which outlines practices, facilities and equipment used with animals infected with human pathogens
- *NIH Guidelines for Research Involving Recombinant DNA Molecules* (NIH, 2002), which outlines requirements for working with animals infected with recombinant DNA
- *Arthropod Containment Guidelines,* Version 3.1 (American Committee for Medical Entomology, 2001), which deal with facilities and practices for working with arthropod disease vectors, including *in vivo* studies
- *Agricultural Research Service Facilities Design Standards* (USDA, 200), which is a good resource for the design of facilities working with agricultural pathogens, including infected animals.

II. GETTING STARTED – RISK ASSESSMENT

In addition to the standard planning and programming exercises that take place prior to the onset of a project, planning for a containment facility must incorporate a thorough risk assessment. Animals add to the difficulty of working safely with hazardous material. Housing, handling, dosing, transporting and husbandry of the animals complicates the control of hazardous material. Hazards in the animal laboratory may include biological agents, toxins, DNA viral vectors, recombinant DNA, chemical agents and radiological agents. Assessment of risks should be the starting place for work safety, and should drive the design of the facility and methods of operation. What are the actual and perceived hazards? How dangerous are they? What is the pathogenicity of the infectious agents, the toxicity of chemicals and the injurious qualities of physical agents? What are the mechanisms of exposure and routes of transmission? What are the infectious/injurious doses, the potential concentration of contamination and the stability of the hazardous material in the environment? What protective measures are needed to prevent or control the hazards? Are there effective vaccines, antidotes or therapies? What would be the impact of exposure to a hazard? What decontamination regimens would be required? A thorough assessment of specific risks is the foundation for determining appropriate and adequate measures for control of risks.

III. ELEMENTS OF CONTAINMENT AND SAFETY

A. Animal Biosafety Levels

Risk assessment for biological agents depends on many factors, and may not be straightforward. Authorities in several countries have developed guidelines placing biological agents into four groups of increasing risk (Fleming, 2000). The guidelines outlined here for biosafety have been drawn in part from the publication *Biosafety in Microbiological and Biomedical Laboratories* (*BMBL*, Richmond and McKinney, 1999). This publication contains a compilation of the knowledge and experience gained by laboratorians over many years, and is recognized worldwide as an authoritative guide for the safe conduct of microbiological research.

Four animal biosafety levels (ABSL1–4) have been described, each with special combinations of safety equipment, facilities, practices and techniques (Richmond and McKinney, 1999). The attributes of these biosafety levels are depicted in Figure 25-1.

1. *ABSL1*

ABSL1 is for non-pathogens; micro-organisms not known to cause disease in healthy adult people. Personnel can safely work with these agents using standard laboratory practices. Lab coats may be worn to protect against general lab contamination, but otherwise no special containment elements are needed.

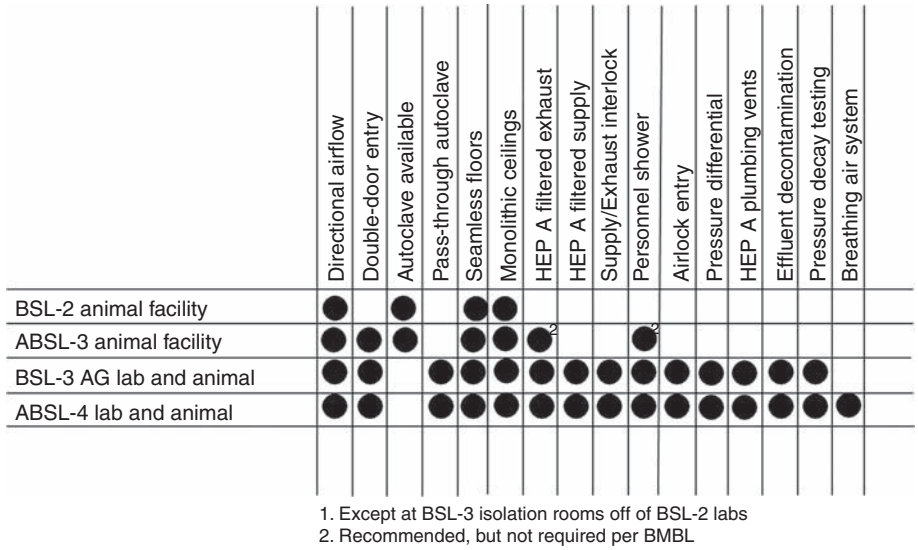

Fig. 25-1 Facility features of biological safety levels.

2. *ABSL2*

ABSL2 is for work with indigenous micro-organisms of moderate risk that are spread by direct contact, percutaneous and mucous membrane exposure, or ingestion. Safe work with these agents requires use of outer protective garments and gloves. Face, eye and respiratory protection may be appropriate. Biological safety cabinets (BSC) may be required when procedures have the potential to create aerosols. Secondary containment elements include locked doors for restricted access, unidirectional airflow into the containment facility, and provisions for personnel and waste decontamination.

3. *ABSL3*

ABSL3 is for work with indigenous or exotic agents that may cause serious or lethal infection. ABSL3 agents have the potential for respiratory transmission, and may cause infection by direct contact, ingestion or aerosols. Work with these agents may require a full complement of standard PPE, including change of clothing. Special PPE may be necessary, depending upon the agent, species of animal and research function (see "Personal protective equipment," below). Secondary containment features may be required for personnel and waste decontamination. Additionally, the facility must include double-door entry and other design considerations to provide directional airflow into the facility from the external environment.

4. *ABSL4*

ABSL4 is for work with dangerous and exotic agents that pose a high risk of life-threatening disease. These agents may be transmitted by direct contact with broken skin and mucous membranes, by ingestion and by respiratory transmission by aerosols. There is no vaccine or therapy available for agents in this class. There are very limited numbers of ABSL4 facilities, almost all of which are operated under strict government oversight. These facilities are generally located in a separate building or are completely isolated within a building. The facilities may be of two types; a BSL 4 Cabinet Laboratory that contains the hazardous materials within a line of Class III biological safety cabinets, or a BSL 4 Suit Laboratory where all personnel are required to wear one-piece positive pressure suits ventilated with a life-support system. These highly specialized laboratories have many special primary and secondary containment requirements.

5. *ABSL3 Enhanced*

An additional category is often referred to, ABSL3 Enhanced. This level has evolved to provide increased environmental protection or increased personnel safety for work with Level 3 agents in special circumstances. ABSL3-Enhanced containment makes some recommended provisions of ABSL3 mandatory for work with specific agents, in specific species or under special research conditions, such as tuberculosis research with infected non-human primates. Mandatory provisions may include HEPA filtered exhaust air, liquid effluent decontamination, decontamination of material using a pass-through autoclave, and the requirement to shower out when leaving. Special primary personnel protection may be required. Risk assessment and response should be the driver for the increased requirements.

6. *ABSL3 Ag*

ABSL3-Ag containment is another category that has been developed and is required by the United States Department

of Agriculture for working with large animals infected with agents that have high environmental consequence (USDA, 2002). These agents may cause serious or lethal consequences to animals, personnel or the environment. For large animals, the primary containment is the room in which they are maintained. Requirements for ABSL3-Ag facilities and operations approach those for ABSL4. Handling, restraint, examination and providing care for large animals with serious infections adds to the complexity of operating in such facilities.

B. Facility Location and Security

1. *Location*

Ideally, containment facilities should be isolated from the remainder of the animal facility or building in which they are located, away from areas of unrestricted access. They should have limited and controlled access for security, public health, animal health and research integrity.

2. *Security and Access Control*

Access to hazard containment facilities should be restricted to those who have received appropriate training and those that require work with infectious agents. Threats posed by persons who oppose the use of animals in research have increased the general security requirements of animal research facilities. Similarly, biocontainment facilities require additional security measures due to the threat of terrorist acts against the USA. Some activities, such as use of primates and "select agents," may increase the probability of threats to security. Risks cannot be totally eliminated, but can be reduced by planning and preventative actions.

Security programs protect physical property, intellectual property, animals and personnel. Security planning should involve all appropriate staff: security, biosafety, scientific, local law enforcement and other operational and safety personnel. The security plan may begin with a security risk analysis that takes into account the mission of the laboratory. Risk assessment should identify potential threats and institutional vulnerability. Vulnerabilities may come from external sources such as assaults, bombs, burglary, fire and civil disturbances, or from internal sources.

The plan should develop goals to be achieved and assets to be protected. Specific measures to implement the plan should be determined by the biosecurity team. Countermeasures for insider threats may include background checks, a two-person rule for containment work, heightened security awareness of the staff, and employee assistance programs. Security measures may include guarded access points; electronic card key, keypad or biometric reader access control; video monitoring; and locks on rooms, storage areas and freezers containing sensitive material. It is very important to ensure access control applies to all who wish access to the restricted areas, including students, visitors, maintenance personnel, animal-care staff and researchers. Times when access is allowed may vary and be restricted, depending on the need and when escorts can be provided. For high-risk facilities, electronic, X-ray and biological screening modalities may be used to scan deliveries. In some cases, off-site delivery may be deemed important, such that all receipts can be inspected before being taken to the laboratory facilities (Richmond and McKinney, 1999; Johnson and Royse, 2002; Richmond and Nesby-O'Dell, 2003). The security program should comply with mandated Federal, State, and local biosecurity requirements, including regulations controlling the possession and use of "select agents," that can cause serious disease in human beings, animals and agricultural crops (USA Patriot Act, 2001; DHHS/CDC, 1996; Public Law 107-188).

C. Staff and Operations

1. *Staff Training, Experience and Skill*

One of the most important factors for safety is a well-trained and experienced research and animal-care staff. They must be proficient in safe research techniques and safe husbandry practices for infected animals. Written policies and procedures should be developed that address the hazards and measures to control and minimize risks. The staff must be aware of the hazards, and strictly adhere to standard operating procedures and safety practices. Mandatory training and competency certification should be required of all persons before access is given to containment facilities and work with hazardous material. If standard practices and techniques are not adequate to control the hazards, they must be supplemented by the use of safety equipment, and by facility features.

2. *Entry and Exit Protocols*

Everything taken into and removed from containment facilities must follow strict entry and exit protocols (Figure 25-2). The containment facility may include multiple air locks for passage of personnel and material into and out of the facility. Personnel may be required to remove their clothes, shower and don protective clothes. This process is reversed when exiting, and is repeated at each entry. Materials that can withstand steam sterilization may be decontaminated by passage through autoclaves. Other materials may be decontaminated using chemicals, and be removed through air locks or dip tanks.

3. *Animal Handling and Husbandry Practices*

Designs for animal containment facilities must take into consideration the kinds of research programs, the species of animals to be maintained and the housing systems to be employed.

a. Rodents

Containment and safety are much easier to accomplish in studies using hazardous agents in rodents than in larger animals. Rodents are more easily handled, and the amount of food, water, bedding and waste to contend with is less. Soiled, contaminated cages, kept intact or bagged if necessary, can be taken to an autoclave for decontamination before removal from the facility.

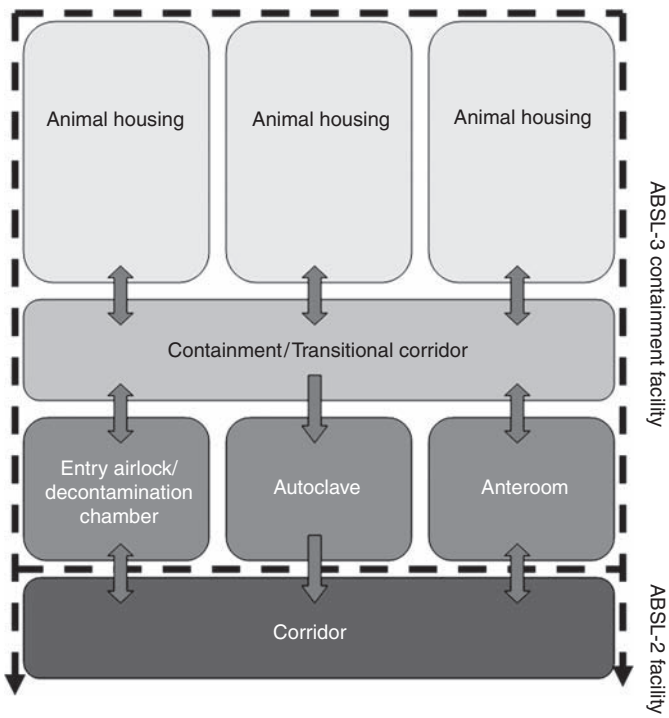

Fig. 25-2 Personnel and material flow in a containment facility.

Many types of containment devices have been developed to provide effective isolation of rodents and small animals. Static isolation cages, used in conjunction with a BSC, are effective as first-line containment for small animals. Such caging incorporates the strategy of multiple levels of containment, "a box (cage) within a box (room)." The cage contains the hazards, protecting personnel and the animal room environment. The BSC provides protection when the cage is opened. The main risk of exposure relates to accidentally dropping a cage. The room protects the environment outside the animal room.

The accumulation of gaseous pollutants in static rodent isolation cages stimulated the development of individually ventilated isolation cages. Many ventilated cages have been developed that have different designs for the air supply and exhaust, not all of which are suitable for containment functions (Lipman, 1999). Some designs have cages under positive air pressure that leak cage-air into the room. Some ventilated cage rack designs attempt to balance air supply and exhaust to each cage; however, it is unlikely that every cage on a multiple cage rack can be perfectly balanced to preclude cage-air leakage into the room. Some ventilated cage systems are specifically designed for containment, and have gasketed, sealed cages or secondary features independent of the cages to provide effective containment (Figure 25-3). Some of these cages have latches that keep the cages intact even if dropped (Figure 25-4). Only static isolation cages or ventilated cages designed specifically to isolate the cages from the animal room should be used for containment functions. Added layers

Fig. 25-3 Containment cage rack. Photograph courtesy of Allentown Caging Equipment Co., Inc.

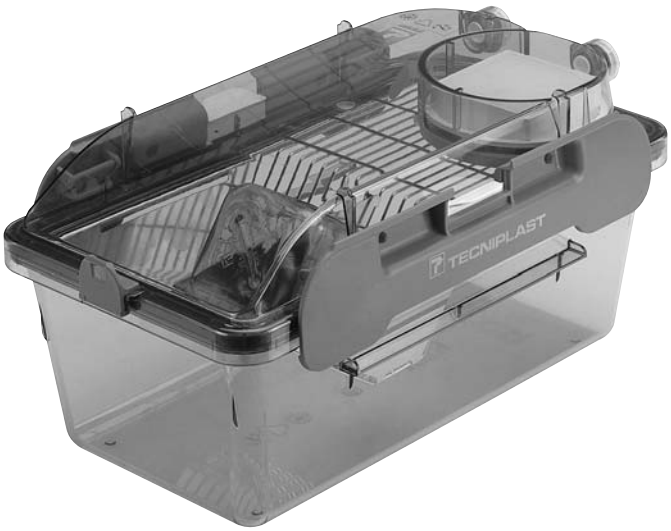

Fig. 25-4 Rodent containment cage.
Photograph courtesy of Techniplast USA.

of containment and isolation of rodents can be accomplished by placing isolation cages into ventilated rigid and flexible film glove boxes; however, these glove boxes can be cumbersome, and add time and effort to standard operating procedures. Alternatively, cages may be placed in isolation cubicles (see "Non-personnel primary containment equipment" section below).

b. Non-rodents

Ventilated Horsfall-type containment units and cages with filtered air supply and exhaust have been developed to maintain monkeys, birds, rabbits and other animals infected with Class 2 and Class 3 infectious agents (Horsfall and Bauer, 1940). These may be fixed or mobile racks with flexible hose hook-ups to the ventilation system (Figure 25-5). While containment cages may be effective when intact, breaks in containment can occur when the cages are opened for daily animal husbandry and research procedures. Husbandry may be somewhat difficult with these cages, and observation of animals may be limited. There aren't biological safety cabinets large enough to protect personnel and the environment when cages containing infected larger animals are opened. Additional protection may be accomplished, as with small animals, by placing the cages in ventilated isolation cubicles. Protocols must be developed and followed to protect personnel, animals, the environment and the integrity of the research, including the time when the cages and cubicles are opened.

In some cases, primary containment of animals in containment caging may be impractical. Protocols for work with infectious agents in monkeys and like-sized non-rodents may be done with animals maintained in open cages. Large agricultural-type animals, such as swine, large and small ruminants, and equines, are not maintained in containment cages but are typically housed in open pens. In these circumstances, the animals are housed in separate rooms by species and infectious agent. The animal room is the primary containment barrier. Protection of personnel who must work directly with the animals is accomplished with the use of conventional and special PPE. Facility design, research and husbandry practices should facilitate containment and control of the spread of contaminated material. Room design generally includes HEPA filtration of exhaust air and, in some cases, supply air. Anterooms or other such spaces may be provided at each animal room for changing and donning PPE and to facilitate appropriate exit protocols. This may involve shower out at the room level.

Fig. 25-5 Primate containment cages.
Photograph courtesy of Primate Products, Inc.

Species-specific accommodations may include floor pens, trench drains and flushing systems. Facilities for large agricultural animals must include means to access and restrain the animals. This may require stanchions, chutes, fencing and gating within the animal room and in corridors outside the animal room. Husbandry techniques may involve hosing down the facility daily. Consideration must be given to decontamination and disposal methods for relatively large volumes of waste, both solid and liquid, and carcasses.

4. *Decontamination Methods*

Proper technique and use of safety equipment will reduce microbiological hazards, but it must be assumed that research with infectious agents will result in contamination of the work area. Decontamination of space as well as equipment and material is of paramount importance in facilities working with infectious agents. Protocols may differ from facility to facility due to size, complexity of the facility, and the agents used; however, the basic requirements and principals remain the same. Surfaces and spaces within the containment facility, especially floors, work surfaces and door handles, must be decontaminated regularly, and everything exiting the containment facility, including personnel, must be decontaminated.

a. Facilities and Equipment

There are four main methods to inactivate micro-organisms: heat, liquid decontaminants, vapors and gases, and radiation (Minshall and English, 1988; Rutala, 1990; Vesley *et al*., 2000; Favero, 2002). Each method may have its application, depending upon the material and objects to be decontaminated, the infectious agent, the amount of organic material present and the resistance of the microbes to specific means of inactivation. Manufacturer's directions for use and safety should be followed for proprietary formulations.

Heat Heat, either dry or moist is one the oldest and most effective methods of inactivating microbes. Autoclaving is widely applicable to sterilize materials that are not heat-labile or when destruction is of no consequence. Autoclaves are usually pass-through units capable of handling full racks and cages. Containment facilities usually have dedicated autoclaves for decontamination of the cages prior to movement through the rest of the animal facility. A wash-down area with steam and hot water should be considered on the soiled side of the cage-wash room to facilitate soaking and loosening of the baked-on material in the cages prior to cage-washing. Large mobile cage racks and pans may have to be initially decontaminated at the room level or placed in sealed carts prior to moving this equipment to autoclaves outside the facility. Material with a high burden of organic matter, such as soiled cages, requires a longer cycle time than when the bioburden is low.

Autoclaves may also be utilized to provide initial decontamination of animal carcasses prior to disposal. Disposal of animal carcasses after decontamination is usually handled by incineration or digestive technologies. The loading of this equipment can occur within the containment area if it is properly designed and dedicated to the facility. If the equipment is outside the facility, the autoclaved carcasses can be double-bagged for removal and disposal. Incinerators have been the historical method of choice for the disposal of carcasses and other waste from infectious disease animal facilities; however, in recent years the environmental requirements and permitting process have made it difficult to upgrade or add incinerator capacities to new facilities. Use of commercial waste disposal companies may be an option in these circumstances. New technologies have been developed, including alkaline hydrolysis tissue digestion, which use a combination of heat and chemicals to dissolve the tissue and bone, producing a decontaminated liquid for disposal. Care must be taken in the discharge of waste to ensure that it falls within the allowable limits of the local municipal sewer system.

Liquid Disinfectants Innumerable brands of liquid disinfectant are available as surface decontaminants. Commonly used disinfectants are alcohols, chlorine compounds, iodophors, phenolics and quaternary ammonium compounds. None are equally useful for all applications, and the presence of organic material may greatly reduce their effectiveness.

Isopropyl and ethyl alcohols, 60–90%, are bactericidal, fungicidal and virucidal. They do not, however, destroy bacterial spores, and do not penetrate protein-rich materials. They may be useful to disinfect clean, hard impervious surfaces.

Chlorine-based disinfectants are available in liquid form (sodium hypochlorite, chlorine dioxide) and solid form (calcium hypochlorite). Household bleach contains 5.25% sodium hypochlorite (52,500 ppm). Hypochlorite solutions of 50–2,500 ppm are used to inactivate microbial agents. Calcium hypochlorite contains 66% chlorine, and has been used in inline dispensers for hose-down applications. Chlorine dioxide is an unstable compound that is prepared by mixing dilute solutions of chlorine and sodium chlorite but is a stronger oxidizing agent than hypochlorite. Chlorine compounds have a broad spectrum of antimicrobial activity against bacteria, fungi and viruses, and are fast acting. They are some of the most widely used liquid disinfectants for surface decontamination, and may be combined with foaming agents that cling to equipment, walls and ceilings to prolong contact for room and equipment disinfection. Although very effective, they are quite corrosive.

Tinctures of iodine have been used as skin antiseptics, but have many disadvantages for surface disinfection in other applications. Iodophors – combinations of iodine with surface-active agents such as nonionic detergents – are non-staining and non-irritant, and are effective as antiseptics and as surface disinfectants. They have a broad spectrum of antimicrobial activity, including activity against acid-fast bacteria and hydrophilic viruses. Iodophors must be properly diluted to have the desired effects. The most widely used iodophor is providone-iodine. Iodophors have been useful for disinfection of instruments, such as forceps used in cage transfer of mice.

Phenol is one of the first chemical disinfectants, and phenolic derivatives are still widely used. Formulations vary in their antimicrobial effectiveness and some are tuberculocidal. Phenolic compounds may cause skin irritation and have other toxic effects.

Quaternary ammonium compounds are organically substituted ammonium compounds with disinfectant and detergent qualities

and low toxicity. Quaternary ammonium compounds have been reported to be bactericidal, fungicidal, and virucidal for lipophilic viruses. They generally are not tuberculocidal or virucidal for hydrophilic viruses. Because of their broad spectrum of action, low toxicity and non-corrosiveness, quaternary ammonium compounds are widely used as surface disinfectants, including use in rodent micro-isolator cage-changing procedures.

Vapors and Gases Fumigation of spaces for decontamination of all surfaces is occasionally required at ABSL3 and generally required at ABSL3-Ag and ABSL4. Gas decontamination requires relatively airtight construction and the ability to isolate the ventilation of the rooms to be decontaminated from other rooms in the facility. This allows the other rooms to remain operational while one room is shut down. Other design features to facilitate fumigation are gas-tight supply and exhaust dampers operated from outside the room (Figure 25-6), electrical circuitry to facilitate decontamination protocols, ports for the injection of gas and neutralization agents (Figure 25-7), and visual access to the areas to be decontaminated. Gases and vapors have been useful for decontamination of large spaces as well as equipment in them.

Formaldehyde vapor may be useful to decontaminate glove boxes or other small, enclosed spaces. It is very effective against a broad spectrum of organisms: bacteria, fungi, viruses, and insects. It may be toxic and carcinogenic for animals and people. Formaldehyde should not be mixed with any source of free chlorine because the more potent carcinogen bis (chloromethyl) ether is produced. Any method of dispensing liquid formaldehyde into the air in suitable quantities is satisfactory. It may be dispensed using various vaporizers and foggers at a dose of 1 ml per cubic foot. The effectiveness of formaldehyde is a direct function of the concentration, temperature and humidity. Temperatures above 75°F and humidity of 70 percent or higher is desired. Formaldehyde is relatively non-corrosive, and equipment that can withstand the high humidity most likely will not be damaged by formaldehyde. A disadvantage of vaporized liquid formaldehyde is that it polymerizes readily on surfaces. The polymers may be difficult to remove, and numerous washes and long waiting periods are required before the treated area is useable. Diluting a standard formaldehyde solution (37%) with methanol (five parts formalin to three parts methanol) reduces this problem.

The fumigant of choice has been formaldehyde gas; however, other fumigants, such as vaporized hydrogen peroxide and chorine dioxide gas, have been successfully used to decontaminate animal holding areas. Each has its advantages and disadvantages. Formaldehyde gas is toxic and has a time-weighted average (TWA) exposure limit (8-hour average) of 0.75 ppm. Formaldehyde gas may be generated by heating flake paraformaldehyde (0.3 g per cubic foot) in an electric frying pan (450°F). Greater amounts must not be used, as concentrations of formaldehyde greater than 8% are explosive (Vesley *et al*., 2000). Treated spaces should remain sealed for 8–10 hours.

Fig. 25-6 Remote air supply/exhaust damper controls.

Fig. 25-7 Port for fumigant gas injection.

Vaporized hydrogen peroxide is a highly effective space and surface decontaminant (Heckert *et al*., 1997). Vapor phase H_2O_2 is an effective sporocide at concentrations from 0.5 to 10 mg/l, and exposure times (30 minutes) and total cycle times (4–8 hours) may be relatively short. Generation of vaporized hydrogen peroxide requires special equipment. A substantial advantage of this system is that the end-products are water and oxygen.

Gaseous chlorine dioxide is a broad-spectrum biocide that is used to decontaminate enclosed spaces and equipment. It is unstable, and must be generated using special equipment. It is sporocidal at concentrations of 1–3 mg/l. It is fast acting; only short exposure times of 30 minutes are required with low residuals. Although a chlorinated compound and an oxidizing agent, it does not produce undesirable and toxic chlorinated organic compounds.

b. Decontamination Procedures: Personnel

Personnel working with infectious agents protect themselves primarily though use of personal protective equipment (PPE). Protective outer garments may be worn over work clothing at ABSL2 facilities and removed as part of the exiting procedure. Clothes should be changed for entry into ABSL3 or greater biocontainment facilities. The clothing, and other articles of PPE worn in such facilities, should be removed before leaving. Effective respiratory protection should be worn. Personnel working at ABSL3 or higher containment, particularly after known exposures or spills, should thoroughly shower with water and soap before exiting the facility.

c. Effluent Decontamination Systems

For infectious agents with higher environmental impact, liquid waste from sinks, floor drains, autoclave chambers and showers in the facility may need to be disinfected prior to discharge into the sanitary sewer system. This disinfection is normally done in a liquid effluent decontamination system. These systems can decontaminate by several methods. The fourth edition of the *BMBL* (1999) and USDA ARS guidelines (USDA, 2002) currently identify heat as the preferred decontaminating method. The USDA does allow chemical decontamination for toilets and showers, if the decontamination can be proven. Most major biocontainment facilities have used heat systems as the basis for design.

Chemical systems are custom designed to model technology used from other industries, such as wastewater treatment and plant water treatment facilities. Advantages include the following:

- chemical systems typically have a lower first cost;
- fabrication times are shorter than other systems;
- no relief vent is necessary;
- only one atmospheric bio-vent is needed; and
- chemical systems are not pressurized.

Disadvantages include the following:

- there may be no single chemical or concentration that will eliminate all the agents;
- chemical systems require high-volume chemical use;
- approval to discharge directly into a wastewater system may be difficult to obtain
- chemical disinfectants tend to coat pipes and valves over time, causing corrosion and continuous maintenance; and
- the certainty of kill is lower if the system is fully automated.

Continuous-flow steam systems inject high-volume, high-pressure steam into reaction vessels with the effluent flow, which vaporizes effluent and then cools and condenses in tube coils prior to discharge. Advantages include the following:

- a steam system that heats up the liquid to a high temperature is a proven way to kill pathogens;
- these systems are specifically designed for use in high-containment facilities;
- there is a high certainty of kill; and
- continuous effluent decontamination (CED) systems are less expensive than the traditional steam systems.

Disadvantages include the following:

- this is relatively new technology;
- systems have a moderate lead time;
- treatment of solids would require an additional component, such as a grinder on the contaminated side, which may be difficult to repair in the event of failure;
- these systems are very complex and require high maintenance and high-pressure steam (usually 120 psi).

A *steam batch cook tank* injects high-volume, high-pressure steam into an effluent holding tank, or uses steam jacketing of the tank to raise the temperature of the effluent. Advantages include the following:

- a steam system that heats up the liquid to a high temperature is a proven way to kill pathogens;
- these systems are specifically designed for use in high-containment facilities and are highly reliable;
- there is a high certainty of kill;
- there is a proven ability to deal with solids in the effluent; and
- these systems require minimal protocol management.

Disadvantages are that these systems have the highest cost and have a long lead time.

In animal facilities where effluent decontamination is required, minimizing the effluent may reduce the size of equipment and operating costs. The liquid effluent may be reduced by using dry systems of husbandry, sink units that capture the effluent in containers that can then be autoclaved, and autoclaves with a built-in effluent-decontamination cycle.

IV. PRIMARY CONTAINMENT EQUIPMENT

Primary containment equipment is intended to protect the immediate environment of the animal room and the personnel working in it.

A. Personal Protective Equipment (PPE)

Personnel working with infectious agents protect themselves against direct contact, mucosal exposure and airborne exposure primarily through the use of personal protective equipment (PPE). This safety equipment includes scrub suits, uniforms, lab coats, gowns, gloves, shoe covers and other protective footwear, head covers, face shields, goggles, masks and respirators. Effective respiratory protection is essential.

Surgical masks may be worn to prevent mucosal exposure of the mouth and nose at ABSL2. They should not be worn for ABSL3 or higher containment operations because their facial fit and filtration efficiency are unsatisfactory for aerosol transmitted agents (Abramson, 1956; Guyton *et al*., 1956). For these applications, N95 respirators that have been fit tested, Powered Air Purifying Respirators (PAPR) or one-piece positive-pressure ventilated suits with a life-support system should be worn as appropriate (OSHA, 1998; McCullough, 2000).

B. Non-personnel Primary Containment Equipment

Equipment that is used to safely hold and handle animals falls into four categories:

1. Containment cages
2. Biological safety cabinets
3. Containment transfer units
4. Cubicles.

1. *Containment Cages*

Containment animal caging is designed to contain potentially contaminated air and other materials that could pose a risk.

2. *Biological Safety Cabinets*

Biological safety cabinets (BSCs) contain splashes and aerosols of infected material generated in husbandry and research procedures. Class I or Class II BSCs may be used for husbandry and procedures with cages that fit within the opening of the cabinet, or for procedures on infected animals where the cages are too large to fit. Richmond and McKinney (2000) have summarized the characteristics and capabilities of various BSC.

3. *Containment Transfer Units*

At times, infected animals must be transferred from their primary caging to safety cabinets for procedures, to surgical facilities, or to imaging suites. During transfer, containment of the animals in transfer isolation equipment should be considered to prevent exposure to infection agents and to prevent cross-contamination between rooms (Figure 25-8).

4. *Cubicles*

In the context of animal facilities, cubicles are essentially small rooms or spaces used to house small numbers of animals in isolation. Larger rooms may be partitioned to contain multiple cubicles, an access aisle and workspace. Cubicle dimensions vary, but they typically measure about 4–5 feet deep by 6–7 feet long to accommodate animal cages for rodents, rabbits, monkeys or other relatively small animals. Cubicles may be built-in and utilize the HVAC system of the facility, mobile units with self-contained ventilation and filtration, or a combination of these (Figure 25-9). Built-in units using the room ventilation have ventilation rates around 20–40 air changes per hour (ACH). Some mobile stand-alone units are essentially Class 100 clean rooms and have up to 150 ACH.

Fig. 25-8 Animal transport isolator.
Photograph courtesy of Germfree Laboratories, Inc.

Fig. 25-9 Freestanding cubicle units.
Photograph courtesy of Britz-Heidbrink, Inc.

Modular, self-contained, drop-in units may have ventilation rates characteristic of either. Cubicles may be operated with negative or positive air pressure relative to their surroundings, with directional airflow into or out of the cubicles, to facilitate a barrier or containment functions. The fronts of cubicles consist of vertical opening doors or divided hinged doors that open out 180 degrees, usually with observation windows of various sizes.

Partitioning larger spaces into cubicles substantially increases the number of available spaces to separate individual animals or groups of animals (Figure 25-10). This facilitates separation of animals by research project, species, experimental paradigm and environmental parameters. Cubicles operated in the negative mode, with directional airflow inward, have been used to isolate infected animals and provide containment of infectious agents. The containment efficacy of cubicles undoubtedly varies with their design, but has been studied and documented very little. Limited reports indicate that cubicles may provide good containment, with essentially no escape of air when the doors are completely closed (White *et al*., 1983; Curry *et al*., 1998). With the doors open, however, cubicles leak air into adjoining space, and this is their major deficiency as containment devices; breaks in containment occur when cubicle doors are open. It is reasonable to assume that hinged doors that open outward may accentuate this phenomenon, as a partial vacuum or suction may occur when these doors are opened quickly, facilitating escape of air.

Cubicles have been used widely for containment of animals harboring hazardous agents, and appear to have been effective, at least for Class 2 infectious agents. The apparent efficacy of cubicles for containment has been attributed to two factors: time of exposure, and dilution of potential contagion. Cubicles are typically opened only for a few minutes per day, and the volume of potentially contaminated air entering a cubicle from the aisle is small relative to the volume of air ventilating the cubicle (Hessler *et al*., 1999). Some data suggest that cubicles can contain airborne infectious agents. Sendai virus did not spread to rats housed in separate cubicles in the same room. Even so, Sendai virus only spread to 15 percent of naive rats housed in open cages in the same cubicle with infected rats (White *et al*., 1983). Sendai virus did not spread to mice housed in the same room in open cages with infected mice (Dillehay *et al*., 1990). Spread of Sendai-virus infection in rodents may therefore not be a valid test of the containment capabilities of cubicles for airborne infectious agents.

Curry *et al*. (1998) utilized computational fluid dynamics methodology to model airflow over a comprehensive range of parameters both within and outside cubicles. Supply of air (20 ACH) high in the cubicle and exhausting the air low, with animals present, resulted in entrapment of the air stream that flowed down one side of the cage rack and up the other side, in a recirculating pattern. Increasing the ACH up to 40 was not sufficient to counter the buoyant quality of hot air from the animals, and the recirculating pattern persisted. Opening the cubicle door resulted in escape of hot air from the top of the cubicle into the room, with coincident flow of cooler room air into the cubicle at a low level.

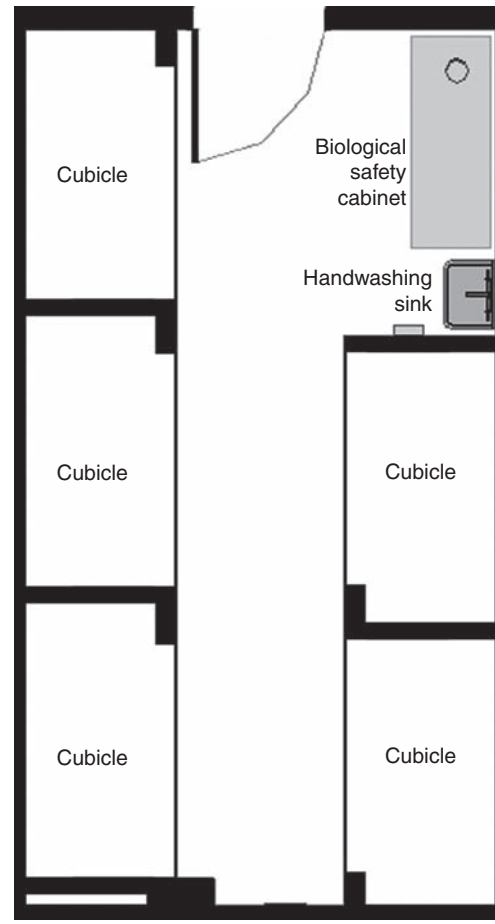

Fig. 25-10 Cubicle room layout.

Curry *et al*. (1998) found that the optimal configuration for minimal turbulence, stagnation and entrainment of air was to supply air (20 ACH) low in the cubicle and exhaust the air high in the cubicle, above the caging. This design capitalized on the buoyant quality of hot air generated by the animals. With the cubicle door closed, air flowed from the bottom supply-diffuser up the cubicle and out via the high exhaust-diffuser in one pass. With the cubicle door partially opened, air within the cubicle was still contained. This air-flow pattern persisted when the cubicle door was fully opened, but hot rising air escaped from the top of the cubicle into the room, although less so than with the high-supply, low-exhaust design. Installation of an air exhaust diffuser in a soffit on the ceiling of the room in front of the cubicle captured hot air escaping from the cubicle, reducing potential contamination in the room. Reduction of air leakage from cubicles may also be effected using Programmable Logic Controllers (PLC). The PLC can be programmed to increase the output of the exhaust loop in the cubicle when the button is pushed to open the cubicle door, increasing the negative pressure in the cubicle (Britz, 2003). It may be that

increasing the height of cubicle above the top of the cubicle door may provide a trap for hot air and reduce air leakage from the cubicles when the door is opened.

Cubicles have, in practice, provided for efficient use of space to isolate animals and to provide containment for Class 2 agents of moderate risk that are not spread by aerosols.

Cubicles designed to minimize escape of air and have cubicle room features that capture escaped air when the cubicles are opened may preclude cross-contamination between cubicles, even with infectious aerosols. Such cubicles may be a practical solution for higher-level containment with small animals or those of moderate size. For all levels of containment, procedures should be used that prevent contamination of space outside the cubicle. Special techniques may be necessary when opening cubicles for daily husbandry or research to prevent transfer of infectious material. Personnel should don appropriate PPE (including effective respiratory protection), one cubicle should be opened at a time, and surfaces potentially contaminated by the husbandry or research procedures should be disinfected, including the room and exterior of the cubicles. Personnel may need to change PPE between cubicles to prevent transfer of infectious agents from one cubicle to another.

V. RESEARCH PROCEDURES

Safety issues may require that exposed animals not be removed and that research support be provided within the containment facility. Restrictions on removal of animals are most likely for dangerous agents that require higher levels of containment, especially at ABSL3 or greater. Support for research procedures with animals such as exposure/infection, treatment, examination, sample collection, imaging, surgery and necropsy may be required. Laboratories to support these functions will have to be included in the containment facility. Multiple projects involving different animal species and infectious agents may be ongoing simultaneously and require the use of the laboratory resources. Decontamination of laboratories and specialized research equipment is paramount for personnel safety, contamination control within and outside the facility, and research integrity. Strategies to deal with infection containment in the research laboratories must entail the same elements of safety for the containment facility: management practices, PPE, special equipment and facility features. Inclusion of dampers within the ventilation system and injection ports on each room will facilitate isolation and fumigation of each space with germicidal gases.

VI. CONTAINMENT OF NUCLEAR AND CHEMICAL HAZARDS

As with biohazards, safely working with radioactive and hazardous chemicals may entail special management practices, protective personnel safety equipment, and specialized containment equipment and facility features. The quantities of radioactive and hazardous chemicals used in animals are usually small, which may minimize the hazard and the necessary precautions. Some work with these agents may be safely done in conventional animal rooms with restricted access, with or without containment caging, and in cubicles or other isolation equipment. Research and husbandry operations that have a great propensity to contaminate the immediate environment with hazardous, highly toxic substances such as methyl phenyl tetrahydropyridine (MPTP) (a chemical used to induce Parkinson's disease in animals) and potent carcinogens may require containment facilities with the features of ABSL2–3. Handling substances in solid form, such as powders that are mixed in animal feed, and disposal of contaminated waste bedding may present the greatest challenges for containment. Special containment mixing devices inside isolation chambers under negative air pressure may be required. Down-draft or back-draft dumping stations may be needed for waste disposal. Transport of soiled caging to washing facilities may require sealed bags or special carts to prevent contamination of facility corridors. Rooms or isolation cubicles in a negative airflow mode may be required to capture hazardous substances or their metabolites that are contained in expired air.

VII. FACILITIES (SECONDARY CONTAINMENT)

Secondary containment elements of the facility are to protect the external environment. The containment facility is intended to keep hazardous material inside the facility, protecting people, animals, and the environment outside the containment zone. Ideally, containment facilities are spatially isolated and away from areas with unrestricted access. Containment facilities may have specially designed and engineered ventilation systems to assure directional airflow from out to in, and air filtration to remove micro-organisms. Other containment features may include controlled access zones with locked doors, air locks with double doors, clothes-change rooms, personnel showers and decontamination equipment.

A. Facility Design

Containment may be provided at the cage, cage enclosure, room and facility levels. Ideally, the design of the facility should provide flexibility for changing requirements. It must accommodate the animal species, caging, husbandry operations and equipment to support the research programs. The containment and decontamination attributes of the facility should be adequate for the function and the highest containment level that is required.

1. *Spaces*

Figure 25-11 illustrates spaces and adjacencies that may be found in a containment animal facility.

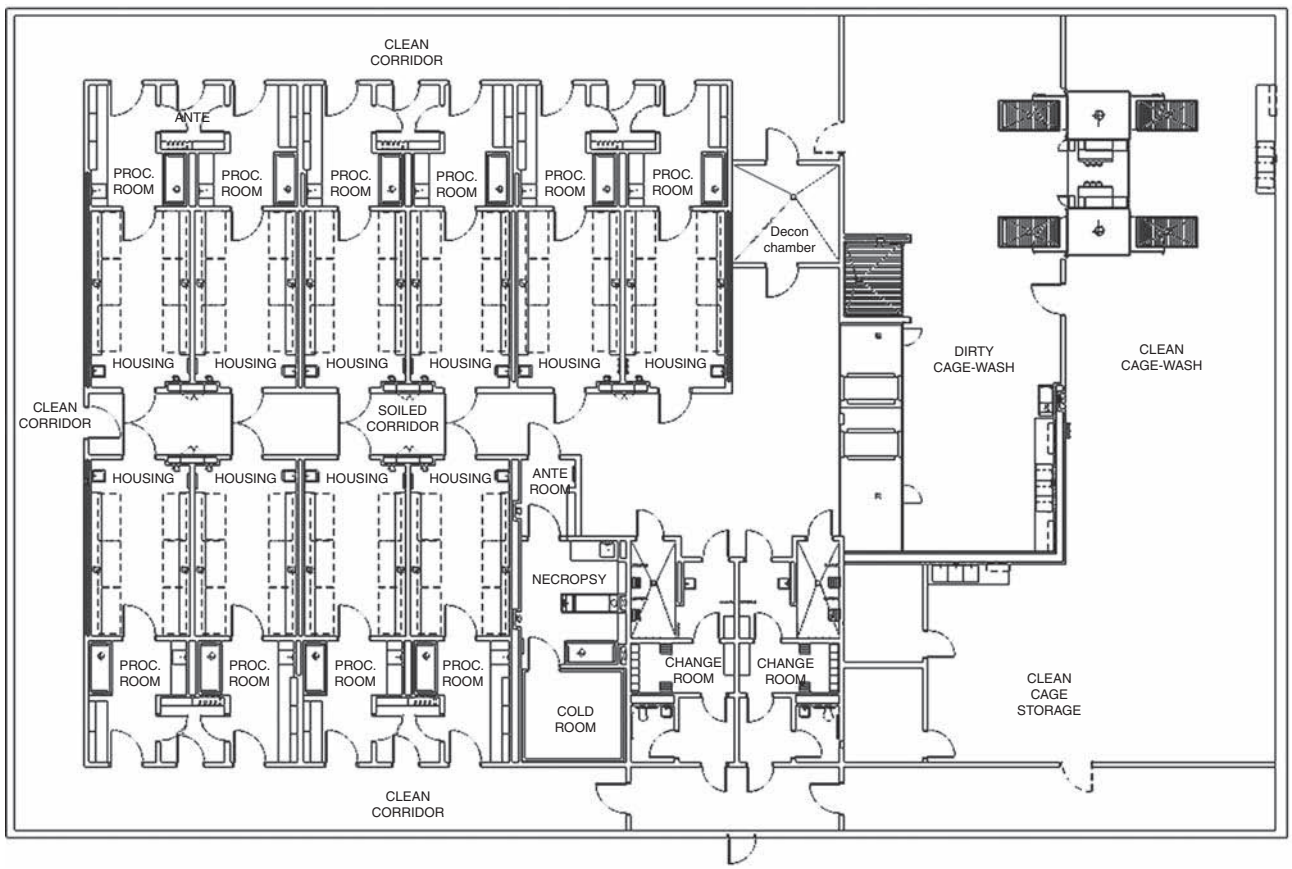

Fig. 25-11 Containment animal facility.

a. Air Locks and Anterooms

As the name indicates, air locks are isolated spaces with their own air supply and exhaust. Air locks require interlocking doors to prevent both from being opened at the same time to facilitate proper function. Anterooms have the same sequential door arrangement, but are not sealed and may use outside air from the corridor rather than having their own supply. Exhaust is still required in an anteroom. Air locks and anterooms provide a secure point of entry into a containment space, and can be used as a place to don personal protective equipment. These spaces also aid in the balancing of the HVAC system by providing a buffer between the positively-pressured corridor and the containment suite. Air-flow indicators should be considered to provide an easy visual means to assess directional airflow. Anterooms and air locks should be sized appropriate to the amount of material and personnel flow they will accommodate.

b. Animal Housing Rooms

Animal housing rooms in containment facilities are not much different from those in a conventional facility. The finishes on floors, walls and ceilings may be subject to impact, harsh cleaning and decontamination solutions. For this reason, selection of durable finishes is important. Masonry units (CMU) often require additional measures such as block fillers, sanding or woven-mesh fabrics to ensure a smooth, easily cleanable final finish. In addition, several types of CMU can be specified to achieve the desired finish. These range from high-density block to lightweight smooth face finishes. Due to the importance of providing a cleanable surface in containment facilities, high build coatings can be installed with mesh or fabric underlayments to provide a smooth finish. Mesh underlayments provide excellent strength and crack resistance, and assist in covering or bridging the many surface irregularities of CMU to help achieve a very smooth final finish.

Establishing and maintaining a good vermin control program is essential for any animal facility, and doors can often be a significant contributor to the harborage of vermin if not properly sealed. Flush, watertight doors are essential in any well-constructed animal facility, and can assist in minimizing the potential for any hazardous or infectious agents escaping the room. Air-pressure resistant doors are essential for containment facilities that must meet USDA BSL3-Ag and BSL4 criteria.

c. Procedure Rooms

Procedure rooms may vary depending on the species and procedures to be employed. For example, small animal housing will typically require a primary containment device for animal manipulation (i.e., a Class II biological safety cabinet), bench space, supply shelves or cabinets, a sink, eyewash, and special gas outlets. Non-human primate procedure space may require exam tables and lights in addition to the design elements mentioned previously. When dealing with larger animals, such as ruminants, the sheer weight of the animals will impact the procedure space design. Hydraulic tables and hoist mechanisms may be necessary to ensure proper safety for the animals and the personnel who work with them.

In typical ABSL2 animal facilities, procedure-room to animal-room ratios may vary from one procedure room for every two animal housing rooms to one procedure room for every four animal housing rooms. Filtered cages, advancements in cage-transport systems, and low hazard risks make working in detached procedure rooms a viable option. However, procedure rooms in higher-containment facilities require additional precautions with regard to material, personnel and animal flows. High-containment facilities may warrant a 1:1 procedure-room to animal-room ratio to better control hazards and maintain containment. Directional air should flow from the clean corridor to the procedure room to the animal housing room. Clean entry and soiled exit anterooms can be added to the suite to better control hazards (Figure 25-12). The addition of anterooms to the entry/exit sequence facilitates directional airflow from the clean corridor to the clean anteroom, to the procedure room, to the animal housing room, to the soiled anteroom/air lock. Once in the soiled anteroom, directional airflow can be either static or negative relative to the soiled corridor if one is employed.

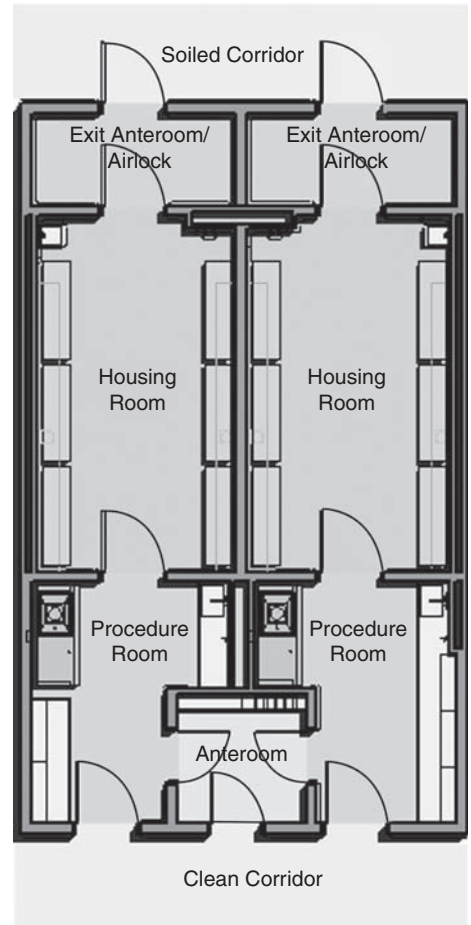

Fig. 25-12 Containment facility housing/procedure suite.

d. Cage-Processing

Cage-washing usually is done in a central cage-processing area outside the containment facility. Material should be decontaminated prior to exiting the containment facility.

e. Mechanical Spaces

Engineering systems play a large role in the proper function of a containment facility. The separation of maintenance personnel from areas of potential hazard assists in maintaining both the proper function of the facility and the high standard of safety for personnel and staff. Design strategies for separation include interstitial floors, mechanical galleries and mechanical corridors.

An interstitial floor can locate most of the electrical, HVAC and plumbing equipment outside the secure perimeter of the potentially infectious animal housing envelope. An interstitial floor provides access to fixtures, filters, valves and other elements that require regular maintenance without exposure to potential hazards. Interstitial floors also eliminate the need for a ceiling cavity in the animal spaces.

Mechanical galleries are another design strategy that can provide ease of maintenance and enhanced safety due to separation. In a mechanical gallery design, the interstitial space is essentially transferred to the same floor as the animal facility. In this design, the filters and valves can still be accessed from outside the secure perimeter; however, a ceiling cavity is required to allow the air distribution ducts to enter the space above each room. While this system provides a high degree of separation for maintenance personnel, expended light bulbs will still require changing from within the room. It is important to provide ample width for the filtration devices in a mechanical gallery.

Mechanical corridors are a third option for providing engineering systems support in a containment facility. Mechanical corridors are very similar to mechanical galleries, but they occupy more space. A gallery design allows the mechanical service to book-end the containment facility, whereas a mechanical corridor system adjoins every room. The mechanical corridor

system also requires ample width for filtration devices, and a ceiling cavity for HVAC equipment. With a mechanical corridor, valves can be placed above the animal housing rooms so long as they are accessible from the mechanical corridor.

B. Mechanical Systems

In animal facilities for biocontainment, as in conventional animal facilities, the facility heating, ventilating and air-conditioning (HVAC) system plays an important role in personnel comfort, experimental control, animal welfare and the control of hazards. In all animal facilities, ventilation rates play an important part in animal husbandry and control of odor and allergens in the facility. However, ventilation rates, while widely believed to be a control of infectious aerosols, have little impact on biosafety, as demonstrated by Chatigny and West (1976) (Figure 25-13). Directional airflow between spaces is much more effective. Air exchange rates should be provided as appropriate for animal husbandry.

Directional airflow, created by zoned pressure differentials between spaces, contains aerosol hazards in the room in which they are generated. Applied experimental microbiology researchers in the United Kingdom have developed a concept called the Laboratory Protection Factor (LPF) that generally indicates how effective containment measures are in achieving contamination control. Their rule of thumb is that adding an anteroom to a laboratory or animal room creates a LPF of 100 from the room where the hazard might be generated. It is projected that the anteroom aerosol contamination would be 100 times less than the contamination in the animal room. It should be noted that if containment caging is utilized with good biocontainment practices, aerosol contamination in the animal room should be minimized. Assuming containment caging and protocols provide a minimum LPF of 100, the anteroom creates an LPF of 100 and the door from the anteroom to the corridor creates and additional LPF of 100, a six log (1,000,000×) reduction in the aerosol contamination from the containment caging to the corridor has been created. If containment caging is not utilized, an additional ante-space might be considered, prior to identifying a space as non-contaminated.

Directional airflow should enter the facility corridor, go into the anteroom and then into the animal holding room, where the air will be exhausted. Where high-consequence environmental-risk agents are used and where the room itself may be primary containment, air locks should be considered rather than anterooms. Since air locks do not allow continuous airflow through the cracks under the doors, they require HEPA filtered transfer grilles, control systems, or special system balancing to ensure containment. As a rule of thumb, there should be a minimum airflow of 100 cfm through doors when opened to maintain directional movement of air.

HEPA filtration of the exhaust from animal rooms is often provided at ABSL3. While not required by the *BMBL* at BSL3

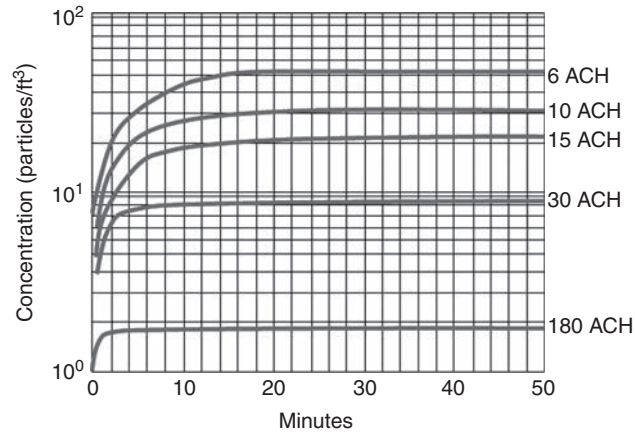

Fig. 25-13 Effect of ventilation rate in air changes per hour (ACH) on particle concentration in a space with continuous particle emission.
Adapted from Chatigny and West, 1976.

unless risk assessment warrants, providing HEPA filtration allows flexibility in the use of agents and procedures over time. A major consideration in the determination of the need for HEPA filtration would be the ability to contain infectious aerosols within primary containment such as containment caging. HEPA filtration of the exhaust air is required for BSL3-Ag animal holding. Double HEPA filters in series may be required for some BSL3-Ag animal holding, and are required for ABSL4 suit laboratories.

HEPA filtration of the supply air is only required for high-consequence environmental risk (BSL3-ag and ABSL4) and when the space is airtight with air pressure resistant doors. Gaps under normal doors to provide directional airflow short-circuit the HEPA filtered supply air if the room is inadvertently positively pressurized. HEPA filtration of the supply air may be warranted if there is a desire for very clean air in the containment facility.

Ventilated containment caging can be recirculated back into the room or exhausted to the outside. If recirculated back into the room, the air should pass through a HEPA filter. In biocontainment facilities, the rationale for connecting the HVAC system directly to the caging is similar to the rationale in conventional facilities. Individually ventilated cages that are directly exhausted separate the cage and room environments. The direct connections should be made in a manner that prevents the inadvertent positive pressurization of the cage relative to the room.

At ABSL2, ABSL3 and ABSL4, biological safety cabinets can be recirculated back into the room, directly exhausted to the outside through the building exhaust system or indirectly exhausted by use of an air gap (thimble) connection. Different types of biological safety cabinets have different exhaust requirements (Richmond and Mckinney, 2000). Class II Type A1 cabinets recirculate HEPA filtered air into the room, and are generally adequate for changing of contaminated cages and other procedures that do not involve flammable or toxic

chemicals or vapors. In instances where small volumes of chemicals are used, Class II Type A2 cabinets with an air gap connection to the facility exhaust system, or Class II Type B1 cabinets may be appropriate. Where larger quantities of chemicals are used, a fully exhausted Class II Type B2 cabinet should be used. It should be noted that Class II, Type B cabinets are rarely required in animal facilities. They also place a heavy demand on building HVAC systems, as they exhaust a large volume of air and operate at a significantly higher system static pressure than do Class II Type A BSCs (NSF/ANSI 49 2002).

Considerations for other HVAC parameters such as cooling and humidification are normally the same in containment and conventional animal facilities. System redundancy is critical in both types of facility; however, in containment facilities redundancy is important to maintain directional airflow and to allow safe continuation or shutdown of procedures in the event of loss of primary systems.

C. Plumbing

Floor drains should be minimized in biocontainment facilities at BSL3 and BSL4.

Where floor drains are used, the *BMBL* recommends that their traps be filled with liquid disinfectant unless the effluent discharges to a liquid effluent decontamination system (Richmond and McKinney, 1999). If risk assessment does not suggest either of the above treatments, consideration should be given to self-priming traps to prevent drains drying out. The negative pressure of containment areas may induce sewer gases into the facility. Where large negative pressures are maintained, consider deep traps.

Animal watering systems for biocontainment facilities are generally no different from those found in conventional facilities. Water sources entering the containment suite should be provided with back-flow prevention or filtration with HEPA-equivalent filters at ABSL3 and ABSL4. Animal watering systems that recirculate water between rooms housing animals infected with different infectious agents should be evaluated for the potential of cross-contamination between rooms with appropriate protection. Gases provided in the containment facility should be similar to conventional animal areas. If gases are piped from outside the biocontainment area, the lines should be filtered with HEPA-equivalent filters for ABSL3 and ABSL4 facilities.

Hand-washing sinks should be provided in containment facilities where protocols dictate the removal of gloves. An option to reduce the number of sinks and to respond to changing protocols is to provide mobile sink units with quick-connect connections. Body showers may be required as part of the protocols for environmental protection. Showers are generally of the pass-through type, with full clothing change areas at either end. Other special plumbing may be required for enhanced containment facilities such as chemical disinfectant showers and breathing air systems.

D. Electrical Systems

The basic electrical systems in containment animal facilities differ little from the systems required for conventional animal facilities. Emergency power is imperative to allow orderly shutdown of biocontainment procedures upon loss of power.

Lighting for biocontainment facilities should be similar to that found in conventional animal facilities. Lighting that is waterproof and vermin-resistant also works well for biocontainment facilities. Conduits serving the fixtures at ABSL3 and ABSL4 should be sealed against passage of air. At higher containment levels, lights accessible from an interstitial space above should be considered.

Electrical service in biocontainment facilities is similar to that in conventional animal facilities. Additional considerations would include the provision of electrical outlets for BSCs, powered containment caging and isolators and recharging of battery-operated PPE.

Requirements for other electrical systems, such as fire alarms, IT service communications and environmental monitoring systems, should be similar to those in conventional animal facilities. The type of agent handled in the facility might dictate the security provided by access control, monitoring systems and closed circuit television systems. If select agents are used, a security plan to prevent unauthorized access to the agents may involve various types of electronic locks.

Care should be taken to ensure that mechanical and electrical penetrations into the containment zone are sealed against the passage of air. Sealing can be accomplished using flexible sealants for small penetrations in low-pressure walls, mechanical seals for piping and rigid sealants such as epoxy for high-pressure differential areas such as ABSL3-Ag and ABSL4. Sealing of penetrations will assist in making the facility vermin resistant.

VIII. COMMISSIONING

The complex systems that support containment facilities must be fully commissioned to ensure that they are working properly prior to the operation of the animal facility. Commissioning for a containment facility should begin during the design process to make sure the systems will perform as designed, and then be tested in the field to make sure that they are installed and operating as intended.

In the commissioning process for biocontainment facilities, particular attention should be paid to directional airflow, controls, and security, alarm and filtration systems. Redundant and back-up systems should be tested in both normal and failure modes to ensure proper operation in the event of system failure. Validation or certification of biological safety cabinets, autoclaves and liquid effluent decontamination cycles should be integrated in the commissioning process. For facilities handling

high environmental-consequence agents, commissioning might include pressure decay testing of the containment shell, including exhaust ductwork and close inspection of the installation of building finishes.

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Chapter 26

Quarantine Facilities and Operations

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I. INTRODUCTION

To be maximally effective in preventing the introduction of undesirable micro-organisms and parasites into colonies known to be free of such pathogens, animal health quality assurance programs must provide for the assessment of health both before and during use in research. Proof of adequate health status from commercial suppliers employing sufficiently rigorous health surveillance programs in conjunction with appropriate exclusion housing often accomplishes the former. However, in cases where the health status of the incoming animals is not known or suspected to be inadequate, quarantine programs are necessary. To quarantine, by definition, is to detain and isolate on account of suspected contagion for purposes of assessment and management of such. Functionally, the goals of quarantine are to protect resident colonies from contagions, safeguard personnel from exposure to zoonoses, minimize the transmission of diseases between animals in quarantine, and optimize the health and condition of the newly acquired animals (Clark *et al*., 1995; Southers and Ford, 1995). Consequently, the facility used for the quarantine program must, by design and operation, meet these needs and also allow sufficient access by select personnel to obtain samples for health monitoring or perhaps limited, controlled access for research purposes.

Depending upon the institution and the nature of research, quarantine facilities may be needed for virtually any vertebrate species, including (but not limited to) domestic rodents, wild rodents, carnivores, livestock, non-human primates, rabbits, reptiles, amphibians, birds and fish.

Information from suppliers related to animal quality should be sufficient to enable a veterinarian to determine the length

of quarantine, to define the potential risks to personnel and animals within the colony, to determine whether therapy is required before animals are released from quarantine and, in the case of rodents, to determine whether cesarean rederivation, embryo transfer or other veterinary interventions are required to free the animals of specific pathogens. Rodents, dogs, cats, rabbits and other species, for example, might not require quarantine if data from the vendor or provider are sufficiently current and complete to define the health status of the incoming animals and if the potential for exposure to pathogens during transit is mitigated.

II. SOURCES OF RISK AND PRINCIPLES OF PREVENTION

The species most often subjected to rigorous quarantine programs requiring isolation are non-human primates and rodents exchanged between research institutions. Although the facilities and rodent management programs employed at academic, pharmaceutical and governmental research enterprises are more advanced with regard to pathogen exclusion and disease prevention than in the past, they are still challenged by a wide variety of organisms (Jacoby and Lindsey, 1998). For example, mouse hepatitis virus and murine parvoviruses may be found in colonies at more than one-third of academic institutions (Jacoby and Lindsey, 1998). This has been exacerbated by the increase in genetically modified rodents, and the sharing of these animals among research institutions has been the genesis for high-level rodent quarantine facilities, equipment and containment practices (Hessler and Leary, 2002). Wild rodents and those from the pet trade that are sometimes used in research present an additional hazard of introducing zoonoses such as hantavirus, lymphocytic choriomeningitis virus, leptospirosis and other diseases (Gregg, 1975; Donnelly and Quimby, 2002; Anonymous, 2003; Smith *et al*., 2005). The current incidence of diseases such as *Pasteurella multocida* in the overall population of rabbits available for research is unknown. In arrangements where reputable vendors supply rabbits meeting research health standards, such as freedom from pasteurellosis, quarantine may not generally be required. There may be a need to quarantine rabbits of unique and rare breeds, however – especially those acquired for research from farms, backyard production operations, auctions or the pet trade.

Between 1972 and 1993, data suggest the incidence of tuberculosis in quarantined non-human primates captured from the wild decreased from 6.6 percent to 0.4 percent (Kaufmann and Anderson, 1978; Anonymous, 1993). Tuberculosis remains a disease risk with severe health and economic consequences; therefore, mycobacterial diseases still must be addressed and managed in non-human primates whether obtained from either foreign or domestic sources. Filovirus infections, particularly in imported non-human primates, are an additional risk (Clark *et al*., 1995). Epidemiologic surveillance suggests a 10 percent prevalence of detectable antibodies in wild-caught macaques and African Green monkeys, which suggests prior exposure and possibly infection with these agents (Anonymous, 1990).

Quarantine and isolation programs may be necessary where unconditioned dogs and cats, such as those from municipal pounds, are acquired by research institutions. While these animals present a risk of zoonotic disease such as rabies, on a daily operative level, less severe infectious agents must also be managed in these species. For example, an epidemiologic assessment of infectious diseases in dogs ($n = 217$) acquired from a municipal pound by Emory University in 1988–1989 demonstrated 35 percent of the animals developing clinical diseases in quarantine and a corresponding 9 percent total mortality rate (data not published). Of those dogs developing clinical disease, 60 percent suffered respiratory system disease (primarily infectious tracheobronchitis, ITB) and 40 percent unidentified mild diarrheal diseases typically responsive to time and anthelmintics. The mean prodromal period from the time of acquisition until the onset of clinical signs (± 1 standard deviation) was 14.7 days (± 11.5 days). Almost all mortality was due to euthanasia of animals with heartworm disease, vicious temperament, or clinical conditions unresponsive to treatment. The rate of spontaneous mortality was 1 percent. In the case of Class B dogs of dealer origin, the incidence of ITB in dogs purchased as "conditioned" was 11 percent, suggesting that additional stabilization and conditioning were necessary. Class B licensees acquire dogs and cats from other sources, including unclaimed animals from animal control institutions, and resell them to research institutions. Likewise, cats of unknown health status obtained from random sources frequently incubate or are actively infected with a variety of pathogens that may be difficult to diagnose, control or manage, including feline leukemia, feline immunodeficiency disease and feline infectious peritonitis (Griffin and Baker, 2002).

The incubation (or prodromal) period of a disease, and its repercussions for quarantine design is important, as it helps determine how the space will be used to manage multiple shipments. If an incoming agent was enzootic at the source institution, detection may take only a few days with sufficiently broad testing. *Bona fide* quarantine periods generally last at least 3–4 weeks, however, because 2–4 weeks is the commonly accepted time period for micro-organisms to proliferate to levels detectable using serology, bacterial culture or molecular diagnostics (Rehg and Toth, 1998; Shek and Gaertner, 2002). Depending upon the agent, inoculum, host age, host genotype and other factors, the development of detectable serum antibodies may be variable, requiring longer quarantine periods – as has been shown in the case with mouse parvovirus (Besselsen *et al*., 2000). Although the tuberculosis dermal hypersensitivity reaction in macaques generally becomes apparent by 4 weeks following inoculation (Clarke, 1968; Schmidt, 1972; Janicki *et al*., 1973), it is noteworthy that almost half of all cases diagnosed in imported macaques occurred after the first month of quarantine (Anonymous, 1993). If some members of an animal

population, particularly rodents, become infected at the time of shipment or receipt, or originated from a colony where they were housed in barrier cages, only a small percentage of animals may be infected (Thigpen *et al*., 1989; Lipman *et al*., 1993; Homberger and Thomann, 1994; Pullium *et al*., 2004). In these cases, infection may be difficult to detect, leading to the requirement for broad sampling of the population and/or repeated sampling conducted over a prolonged period of time. The risk of contamination during shipment has been observed at 1.5 percent for rodents shipped by air (Rehg and Toth, 1998). While this may seem low, the costs of management of an infectious disease outbreak can be exponentially greater if the pathogen is inadvertently released into the facility at large, rather than confined to quarantine (Rehg and Toth, 1998). Where many shipments may be received into quarantine, the facilities should be sufficiently spacious and compartmentalized to permit animals from one shipment to be effectively separated from animals from other shipments, in order to preclude transfer of infectious agents between groups.

Depending upon the nature and circumstances of the research and quality of the supplier, there may also be a need to isolate and quarantine livestock, especially if animals are received from multiple, disparate sources and mixed after arrival. Swine may be obtained from high-quality suppliers of specific pathogen-free stock, but, depending upon geographic locale, access to such sources may be variable. Disease caused by *Bordetella bronchiseptica*, *Hemophilus parasuis*, *Pasteurella multocida*, various enteric organisms, and other agents can afflict the weaned farm-origin pigs that are sometimes preferred for research (Hansen, 1997). As swine emerge in importance as a source of tissues and organs for xenotransplantation, the need to maintain swine of "xenograft-defined" microbiological status under stringent exclusion and containment conditions will be paramount (Swindle, 1998; Boneva and Folks, 2004). *Coxiella burnetii*, the highly infectious causative agent of Q fever, is widespread in ruminants worldwide, with human infections reported in virtually every state in the United States (McQuiston *et al*., 2002). Quarantine programs have also been advocated for marsupials, reptiles, amphibians, domestic and wild-caught fish, and wild birds (Jurgelski *et al*., 1974; Wolff, 1996; Astrofsky *et al*., 2002; O'Rourke and Shultz, 2002; O'Rourke and Schumacher, 2002; Stoskopf, 2002).

Diseases can be transmitted between animals by a number of routes, including aerosol, direct contact, feco-oral or inanimate objects (fomites). The ubiquitous mouse hepatitis virus (MHV), murine noroviruses (MNV) and continually emerging parvoviral infections of rodents involve transmission by many routes, including both airborne and feco-oral for MNV (Wobus *et al*., 2006) and MHV, and ingestion and close contact for parvoviruses such as murine parvovirus (MPV) (Smith *et al*., 1993). *Coxiella burnetii* can be excreted at high levels from sheep during parturition, and transmitted by aerosol to humans over long distances and in small quantities (Lyytikainen *et al*., 1997). Common respiratory diseases of dogs and cats, such as ITB and feline respiratory disease complex, are likewise transmitted by aerosol and direct contact. The threat, however, does not end with the animals themselves. Away from animals, a number of pathogens can persist in the environment and on contaminated fomites for days to weeks at a time or even longer, including agents such as parvoviruses, picornaviruses, dermatophytes, bacterial spores, nematode eggs and the like. The management and prevention of transmission by these routes and others, such as skin puncture and mucous membrane exposure from splashes, must be addressed in the design of facilities. A number of items used in quarantine can become contaminated and, if not properly handled or decontaminated, these items represent a risk for dissemination of contagions out of quarantine, into the facility and beyond. Transmission via fomites can be by either aerosol or non-airborne mechanisms. Consequently, the prevention of transmission of agents via inanimate objects exiting the area must also be considered in the design and operation of quarantine facilities. Potential fomites that may be encountered in the context of quarantine operations include clothing, sharps, soiled cages and bedding, used water bottles, shipping containers, other forms of solid waste, diagnostic specimens, scales, veterinary examination equipment, clippers and sanitation supplies.

III. GUIDELINES AND RECOMMENDATIONS

The acquisition and quarantine of animals used for research purposes may fall under certain tenets and laws. It is for reasons of protecting the public health and food supply, and for wildlife conservation, that the US federal government and some states have regulated the importation or movement of certain species across national and state lines, respectively. The approach to quarantine can be conveniently divided into that intended for species of foreign versus domestic origin. An additional division can be made along the discriminator of non-human primates versus all other species. Unlike most other species used in research, non-human primates often come from a wide variety of sources, have a poorly defined health status and harbor unknown flora, thus representing a significant zoonotic hazard (Southers and Ford, 1995).

Exposure to imported NHP presents infectious disease risks, which may include emerging infectious diseases such as Ebola-Reston, Cercopithecine herpesvirus 1 (B Virus), monkeypox, yellow fever, Simian Immunodeficiency Virus, tuberculosis and other diseases, some of which may not yet be known or identified. Since 1975, the Federal Quarantine Regulations (42CFR71.53) have restricted the importation of non-human primates under the aegis of the Centers for Disease Control and Prevention (CDC) (Anonymous, 1990, 1991; DeMarcus *et al*., 1999). In consideration of imported non-human primate quarantine, the federal government has not defined quarantine-facility design standards or construction criteria. Consequently,

in the rare case where such a facility may be contemplated, the design team should contact the Division of Global Migration and Quarantine, National Center for Infectious Diseases, CDC, Atlanta, GA. Additionally, there may be state laws, regulations and policies governing the entry and use of NHP (Johnson *et al*., 1995).

The importation of reptiles, fish and endangered species is regulated by the US Department of the Interior, Law Enforcement Division, Fish and Wildlife Services. The United States Department of Agriculture (Veterinary Services, Animal and Plant Health Inspection Service) has responsibility for livestock, dog and cat entry into the United States. Institutions and design management teams seeking to import these species from sites outside of US borders should properly consult with the appropriate federal agency. The federal government does not regulate the importation of rodents or rabbits, provided they have not been inoculated with any pathogens for scientific purposes.

IV. QUARANTINE GOALS AND GENERAL DESIGN CONSIDERATIONS

In determining the need for quarantine facilities, the operator should consider the goals of the veterinary medical management program. For example, the type and size of space, support equipment, monitoring and security may be vastly different if the intent is to permit otherwise presumably healthy animals to restore physiologic homeostasis for a few days after the stress of shipment and receipt than if it is the stabilization, health characterization and appropriate veterinary medical management of wild-caught animals acclimating to confinement. Given the possibility of a broad spectrum of scenarios, professional judgment should be used, applying the contemporary practice standards of laboratory animal medicine (Clark *et al*., 1995). Situations may be addressed differently depending upon the species to be quarantined. For many species, quarantine may be conducted by the research institution or by contracting commercial entities to provide the technical services. Consequently, a principal decision is whether to build, renovate or dedicate space to a quarantine activity, or to outsource such activities to qualified contractors.

Stabilization following shipment of research animals, particularly rodents and rabbits, of a defined and consistent health status from a commercial production barrier generally requires 3–5 days (Dymsza *et al*., 1963; Gisler *et al*., 1971; Wallace, 1976; Landi *et al*., 1982; Toth and January, 1990; Van Ruiven *et al*., 1998). This may be done in a typical housing room with resident animals, or in a separate isolated area. For the purposes of this chapter, "stabilization" following shipment is considered to be only daily observation of the animals, as opposed to the more intensive health status evaluation and monitoring that occurs during quarantine, and will not be discussed further.

It is clear, however, that other species, such as carnivores from municipal pounds or Class B dealers, non-human primates, farm animals, rabbits of unknown health background and certain other species, may require conditioning and quarantine programs lasting from a few days to several months. Ordinarily this should be accomplished in a dedicated area that has been physically and programmatically isolated from more stabilized animals and from persons whose duties do not require contact with other animals.

While there are no thumb-rules or formulas for the size of quarantine facilities, in order to minimize the time that caretakers and other users are in the quarantine area and reduce the risk for containment failures due to human error, the space should be sufficiently large and designed for efficient use. For example, although often overlooked or under-allocated, adequate storage space should be provided for janitorial supplies (including disinfectant, mops, buckets and personal protective equipment) and staging or storing clean and dirty cages and other materials. Where procedures other than passive observation are intended for the quarantine facility, the design should enable multiple persons to work simultaneously without jostling or creating close-contact situations that precipitate spills or accidents with sharp objects.

Non-human primate quarantine may involve importation into the country – a situation strictly regulated by CDC at only approved sites – or secondary quarantine, at a research institution for domestically-bred animals or those acquired through an approved importation site. Facilities used for these species, whether primary or secondary, should be designed with sufficient space and rooms to enable the animals to be isolated by species and date of acquisition, remain secure, and facilitate room decontamination. Facility layout should allow for an individual group to progress through a quarantine period lasting 1–3 months intact as an entity. In cases where the volume of the operation will involve high throughput and multiple shipments, there should be sufficient rooms or autonomous compartments to prevent mixing of animals from different shipments in order to prevent the obligatory restart of the quarantine period (Manning *et al*., 1980). A site with several small rooms offers greater flexibility, and is preferred over arrangements with only one or two large rooms. An advantage related to non-human primate quarantine is that the procedures are well-standardized and generally consistent from institution to institution, and there are numerous existing facilities with which to benchmark, thus enabling the design to be a relatively straightforward process.

The same situation, unfortunately, does not exist in rodent management, where the ideal program remains specifically undefined, and detailed industry-wide standards have not been developed. Consequently, quarantine programs for rodents, as run by different research institutions, are essentially large, grand experiments under a constant state of evaluation and adjustment. In considering quarantine design, attention should be given to the regularity of incoming shipments, the average batch size and mean total quarantine census, the housing method, and the duration of the isolation period. The space dedicated to quarantine should allow for cage-change stations and the safe conduct of

diagnostic sample collection, and some flexibility to enable limited experimental procedures such as tissue collection or simple surgeries. At Emory University, where mice are received into quarantine on a weekly basis, batches are typically moderate in size (3- to 10-cage range), barrier technology is used at the cage level, and the quarantine period lasts 8–12 weeks. Space for this activity is dedicated to accommodate 1–3 percent of the total institutional mouse-cage census or the equivalent of 2 percent of the total net square footage for mouse housing. Another approach is to use a ratio of the number of cages in quarantine per overall number of scientists at the institution using the given species; however, such benchmark data have not been developed. These methods might not apply to small institutions with a low rodent census and infrequent gift rodent exchanges, and likewise may not apply to large (>20,000-cage census) operations. It is important to appreciate that institutional rodent quarantine programs are expensive, often adding substantial levels of complexity and impediment to collaborative research (Grimm, 2006), and the ideal would be to facilitate gift rodent exchanges using embryo transfer or equivalent technology. As institutions with the financial wherewithal and in-house resources convert significantly to trading embryos or sperm or other biological materials rather than live mice, less space will be needed for rodent quarantine. Given that some mice are used for acute or short-term studies and that not all sources will have the wherewithal to bank and ship embryos, sperm or the like, it is not realistic to believe that all live mouse shipments will become obsolete.

While some livestock and many dogs and cats acquired for research may not require formal quarantine management, those acquired from random sources of uncertain health status, possibly including Class B dealers, are a different situation. Quarantine periods of 8–12 weeks are recommended for random-source cats (Griffin and Baker, 2002). The aforementioned experience at Emory University with unconditioned dogs, particularly the considerable variation around the mean for the onset of clinical signs of disease, suggests that relatively lengthy quarantine periods (e.g., 24-day minimum) are warranted and should be considered. While different institutions and programs would approach this situation in diverse ways, given that most dogs remained asymptomatic, the authors' approach was to relocate dogs stepwise through a series of three rooms dedicated to quarantine as they underwent preventive medical procedures. Through time, the animals were moved into rooms containing populations of progressively healthier dogs as they became increasingly stabilized over a 24- to 30-day quarantine period. The management of newly received swine and small ruminants should be considered in the same light of quality of source, number of sources, anticipated use and the like as for dogs and cats.

Reptiles, fish and amphibians are often isolated at the enclosure level or in simple isolation rooms for periods of a month or less using standard operating procedures and typically no other specialized quarantine architectural features, and won't be discussed further here.

V. LOCATION AND DIMENSION OF PHYSICAL SPACE

Quarantined animals, whether at the room or cage level, should be effectively isolated, both physically and programmatically, from other animals at the institution. Although the concept of physical isolation is straightforward, the location and design of the physical space can influence the operation of quarantine programs on multiple levels. The ideal is to locate quarantine facilities completely separated from resident colonies in a stand-alone structure (Hessler *et al*., 1999; Bernacky *et al*., 2002). Where a separate building is not possible, quarantine should be located in space at the building periphery, near the receiving area (Ruys, 1991) but isolated within secure confines away from major foot traffic thoroughfares (Southers and Ford, 1995; Hessler *et al*., 1999) (Figure 26-1). Where quarantine is remote from the receiving area, animal delivery into quarantine should

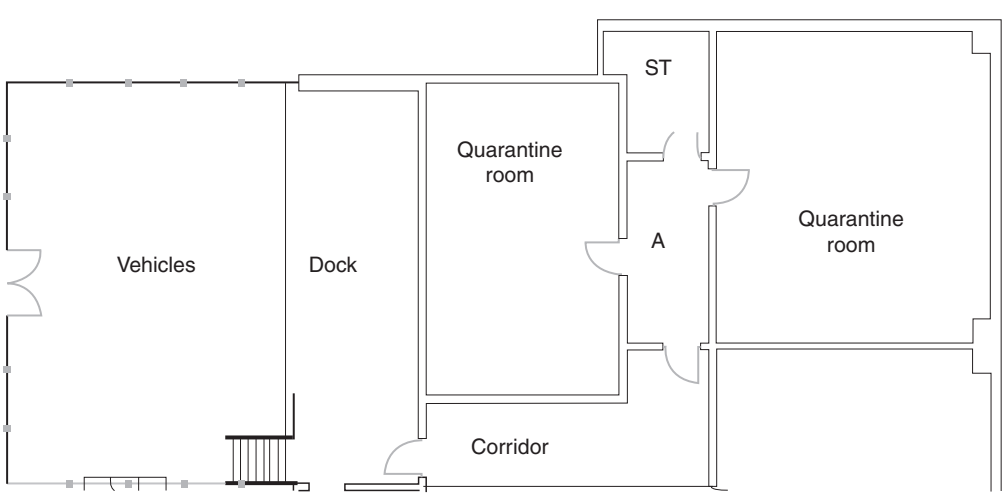

Fig. 26-1 Floor plan depicting a duplex room arrangement suitable for quarantine, isolated at the periphery of a building, convenient to a loading dock and also showing storage (ST) and an anteroom (A). Figure courtesy of Emory University, Atlanta, GA.

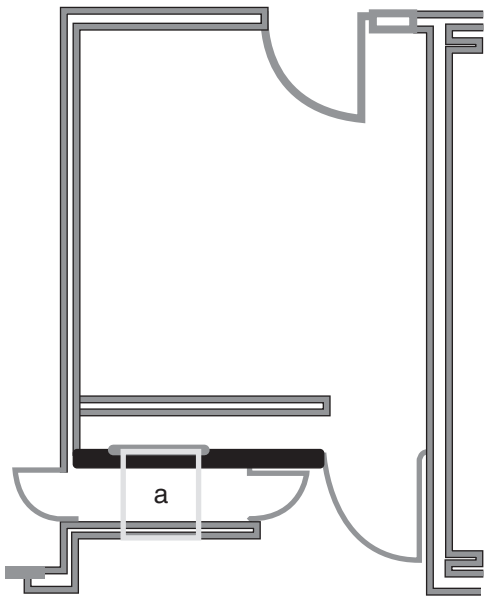

Fig. 26-2 A single quarantine room layout suitable for small populations or irregular quarantine activity. The built-in, pass-through autoclave (a) makes this arrangement well-suited for rodent isolation.
Figure courtesy of Emory University, Atlanta, GA.

be through a corridor system designed with differential air pressures, preventing contamination of other areas of the facility (Southers and Ford, 1995). Quarantine operations are facilitated by a location within reasonable proximity of the cage-wash, autoclaves, necropsy and animal-carcass storage facilities.

VI. GUIDING PRINCIPLES OF DESIGN

Following location and allocation of square footage, the next quarantine consideration is selection of the general layout. The design of the space should allow for flexibility in use and take into account the various species requiring isolation, the prospect of multiple acquisitions, the duration of quarantine periods by species, and the housing method. Quarantine facilities should allow for physical separation of animals by species to prevent interspecies disease transmission, and is usually accomplished by housing different species in separate rooms (Clark *et al*., 1995). Where intraspecies separation is essential, such as when rodents are obtained from multiple sites or sources and differ in pathogen status, suites of rooms or cubicles are preferred. Suitable alternatives are laminar-flow units, cages that have filtered air or separate ventilation, and isolators, particularly for rodents, providing the species are otherwise behaviorally compatible (Clark *et al*., 1995). Keeping in mind that not all institutions are blessed with perfectly designed quarantine areas, or the resources or even the scientific demand to dedicate one to full-time use, there are times when objectives must be accomplished within the scope of the resources available. In this case, the availability of

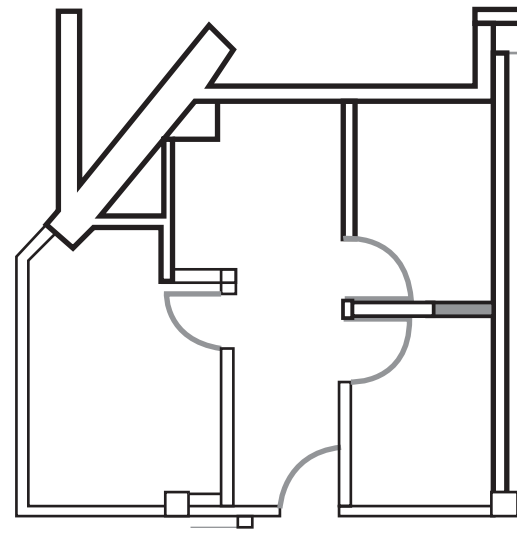

Fig. 26-3 Multiple room suite arrangement allowing for multiple lots or shipments of animals.
Figure courtesy of Emory University, Atlanta, GA.

programs and other infrastructure to compensate for inadequate space or design becomes the key determinant in the success of the program, and often depends upon staff making a challenging situation work through strict adherence to effective standard operating procedures. Given these considerations, there are three general options for quarantine layout: a single room, a suite of rooms or a suite of cubicles.

A single quarantine room, providing that it is relatively spacious, is most suitable where shipments are irregular, and for small institutions with a modest census and little prospect for high-volume activity (Figure 26-2). Single rooms may be sufficient for livestock, dogs, cats, non-human primates and rabbits, and for rodents confined in barrier cages or isolators. Oftentimes a secured room with negative differential airflow relative to the corridor and otherwise meeting *Guide* construction specifications may be appropriate (Hessler *et al*., 1999). For example, for livestock, carnivores, rabbits and non-human primates, it may be appropriate to house a received batch in a standard animal housing room under quarantine standard operating procedures and to allow the room to revert to normal use once quarantine is completed without relocating the animals. In an agricultural setting, this concept might be as simple as locating barns, loafing sheds, paddocks and pastures for newly received animals physically separated from and downwind of more stabilized animals. An additional consideration, however, is that some airborne diseases, particularly Q fever (Lyytikainen *et al*., 1997), can be transmitted over great distances, and even from farm to farm.

Where multiple species are acquired in regular shipments and potentially in large consignment, a suite of quarantine rooms allows for "all in – all out" management (Figure 26-3). In cases where there may be regular deliveries of a small number of large animals, a series of rooms may enable individual

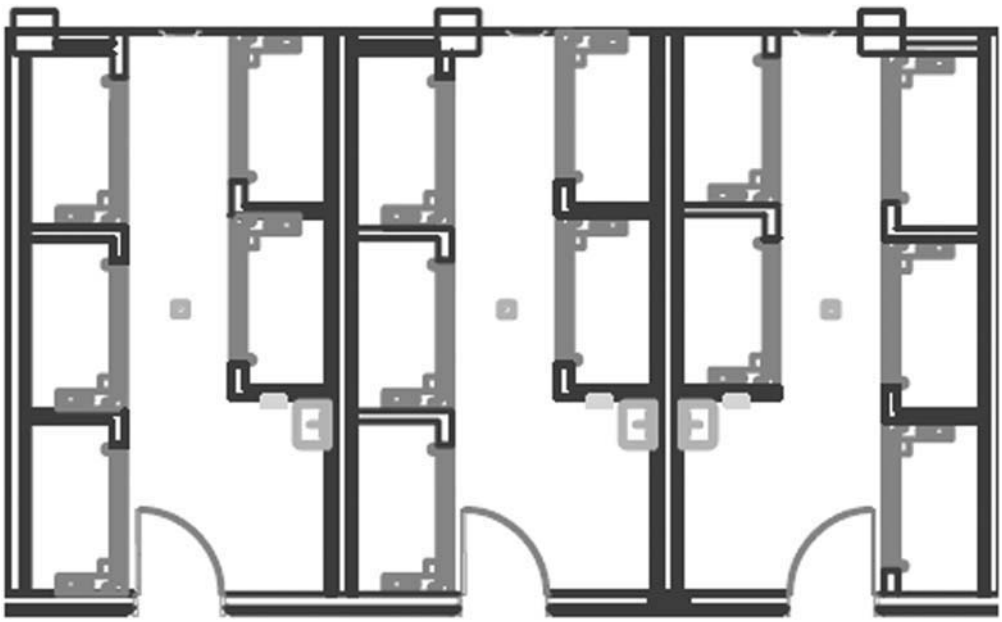

Fig. 26-4 Floor plan showing three suites of cubicles allowing for flexible use of space including quarantine, and particularly where small numbers of multiple species may require isolation or small batches or regular shipments of rodents are received.

Figure courtesy of Emory University, Atlanta, GA.

or groups of animals to be relocated from room to room as they become progressively stabilized, receive increasing amounts of preventive medical procedures (e.g., vaccines), and their health characterization becomes defined and acceptable. For rodents, one or more large rooms can be used to accommodate animals in barrier (filter top) cages or, providing there is sufficient space and power, portable laminar airflow rack isolators (i.e., Bioclean Units) or flexible film isolators.

Suites of cubicles enable efficient and flexible use of a relatively small space, where multiple species are obtained and quarantined in small batches or regular shipments (Ruys, 1991) (Figure 26-4). Optimal cubicle ventilation resulting in minimal turbulence, stagnation and entrainment has been found to be provided by delivering 20 air changes per hour via two opposed sidewall diffusers located low on the wall, and with exhaust high in the cubicle on the back wall (Curry *et al*., 1998). Cubicles are wasteful of space when the suite is devoted to only one species and do not promote efficiency of rodent operations when they contain large numbers of cages, as it is difficult to move racks, access biosafety cabinets and process large numbers of clean and soiled materials without extensively widening the central corridor. For the same reason, it is cumbersome to move racks to transfer non-human primates from soiled to clean cages in the often close confines of a cubicle suite. The control of airborne cross-contamination between cubicles can be compromised when doors are opened unless a cage-level form of containment is used. This risk can be obviated to some extent with meticulous adherence to sensible practices that prevent cross-contamination. These include keeping all the cubicle doors closed, opening only one door at a time, and minimizing the time any one door may be open (White *et al*., 1983). It bears noting the one infectious disease study validating the effectiveness of cubicles in pathogen containment was based upon Sendai virus (parainfluenza type 1) infection of rats (White *et al*., 1983). Compared to other agents, such as coronaviruses (e.g., MHV, SDAV), subsequent experience has shown Sendai virus to be of low transmissibility, except under conditions of close contact (Dillehay *et al*., 1990; Homberger and Thomann, 1994). The reliance upon Sendai virus may not have allowed a suitably rigorous assessment of cubicles as containment devices. In the case of rodents, cubicle systems should be shown to be effective in the containment of highly infectious agents (such as coronaviruses and pinworms) before being relied upon as the primary means of containment. Until then, the role of cubicles should be as a secondary containment component in support of cage-level barrier systems.

For rodent quarantine, a fundamental decision is whether to use isolators or cage-level barriers. Microbarrier (filter top) cages used in conjunction with Class II biological safety cabinets whenever cages are opened have been repeatedly shown to be effective in pathogen containment (Lipman *et al*., 1982, 1987; Dillehay *et al*., 1990; Boylan and Current, 1992; Whary, 2000; Whary *et al*., 2000), and can be flexibly used both in rooms and cubicles. It is the preference of the authors to use non-ventilated (static) cages in rodent quarantine, as individually ventilated cages (IVC) pose the risk of environmental contamination from exhaust air leaking from cages. Others might consider this risk to be negligible (especially with gasket-sealed cages), or find the labor savings associated with IVC to be more cost-effective.

Gas-tight flexible plastic isolators (Figure 26-5) can be used for containment purposes in rooms, but, owing to their size, are generally not suitable for cubicles. Isolators are portable, well-suited for cesarean rederivation procedures, and offer the flexibility of subdividing common, generic space for different uses. They may be especially useful where a physically isolated

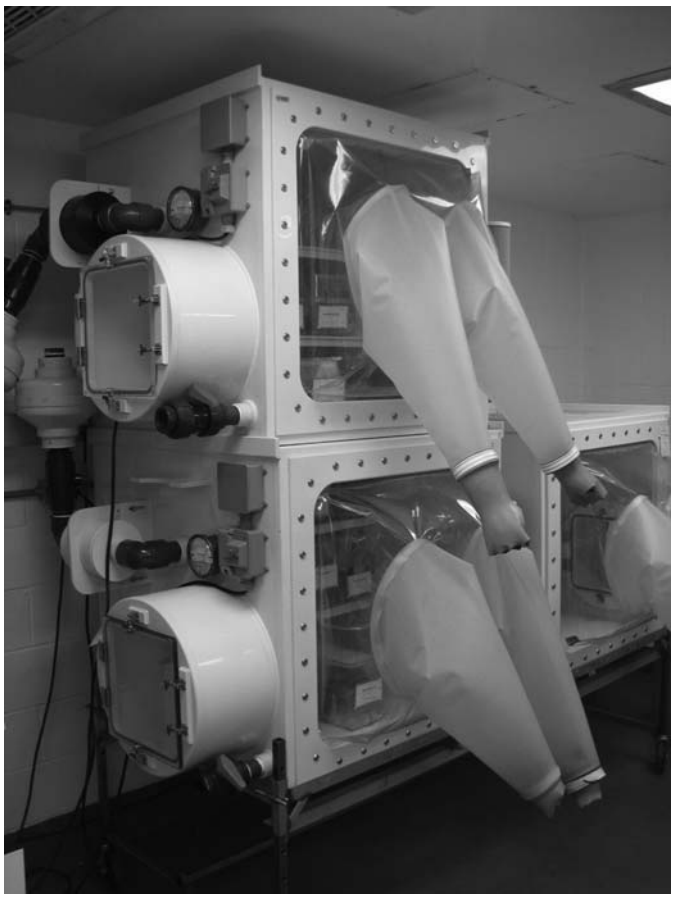

Fig. 26-5 Stacked semi-rigid isolators suitable for rodent quarantine activities.

Photograph courtesy of Mt. Sinai School of Medicine, New York, NY.

quarantine facility is not available. Isolator technology has a proven track record for being used effectively and economically by commercial producers of rodents on an impressive scale. Prepackaging of materials, including food, water and bedding, enables efficient use of the units. Disadvantages are that these units are labor-intensive, especially for the inexperienced or infrequent user, or where there may not be the advantage of economy of scale. In addition, glove dexterity can be less than ideal for certain purposes. While offering greater species flexibility than microbarrier cages, there are limitations to the size of animals that can be accommodated in isolators. Purchase cost may be a disadvantage, but the potential user should consider the price in light of the lifetime operating costs compared to other options.

VII. ARCHITECTURAL FEATURES

If the intention is to build, renovate or designate a specific area for quarantine purposes, there are many important general elements to consider. Due to the high cost of construction or renovation of such spaces, the approach to design should be pragmatic (Ruys, 1991) and based upon legitimate risk. As pathogens may be transmitted by a variety of mechanisms, including aerosol, the physical design and operation of quarantine areas for animals of uncertain health status should ideally utilize as many of the design principles of animal biosafety level 3 (ABSL3) containment as possible (Hessler *et al*., 1999; Chosewood and Wilson, 2007). While the vast majority of animal pathogens pose no health threat to humans, many agents represent an airborne threat from one individual to another of the same species, and sometimes even other genera. A facility built to ABSL3 standards would consist of a sealed room or suite of rooms with air- and waste-handling facilities; facilities for the decontamination of personnel and for disinfection or sterilization of soiled implements and equipment; entry and egress through air locks; and back-up power. Where the ideal cannot be realized, the facility minimally should be designed to operate at animal biosafety level 2 (ABSL2) (Chosewood and Wilson, 2007). These facilities are especially effective when additional layers of protection are employed, such as when flexible film isolators or barrier-level caging systems are used within the facility. Except as described below, all other construction criteria and specifications for architectural features, plumbing, electrical and mechanical systems are the same as given in the *Guide* for standard animal housing (Clark *et al*., 1995).

Quarantine areas for non-human primates and rodents ideally should require entry and exit of personnel through an anteroom with two sets of doors (Hessler *et al*., 1999; Rahija, 1999), preferably via an airlock or incorporating an air shower (Figure 26-6). One advantage of cubicle suites is that the corridor can serve as a nominal anteroom (Figure 26-4). Where an airlock exists, interlocking hardware should permit only one door to be opened at a time (Hessler *et al*., 1999). The anteroom should contain sufficient space to accommodate a handwashing sink, trash receptacles, and an area to stage racks, cages, supplies and implements either entering or exiting the area. In the efficient management of rodents, the design should provide for enough space to permit the storage of a full complement of complete, intact cages. As an alternative, the anteroom should be sufficiently spacious to contain and allow the passage of a fully loaded rack of caging materials without interfering with the doors (Hessler *et al*., 1999). Assembling cages from separated components in quarantine should be avoided, as it theoretically risks contamination of clean cages and transmission of infectious agents.

The integration of walls, floors and ceilings should be conceptualized as an envelope with sealed ducts, plumbing, conduits, wiring, lights, and any other surface penetrations, to reduce air escape and permit decontamination by fumigation or other means. As such, the perimeter walls should extend to the floor above (Hessler *et al.,* 1999). In extreme, high-risk cases, it may be useful to design a double-wall system utilizing an air lock and progressively differential air pressures (Ruys, 1991). Construction may need to be more substantial and damage-proof

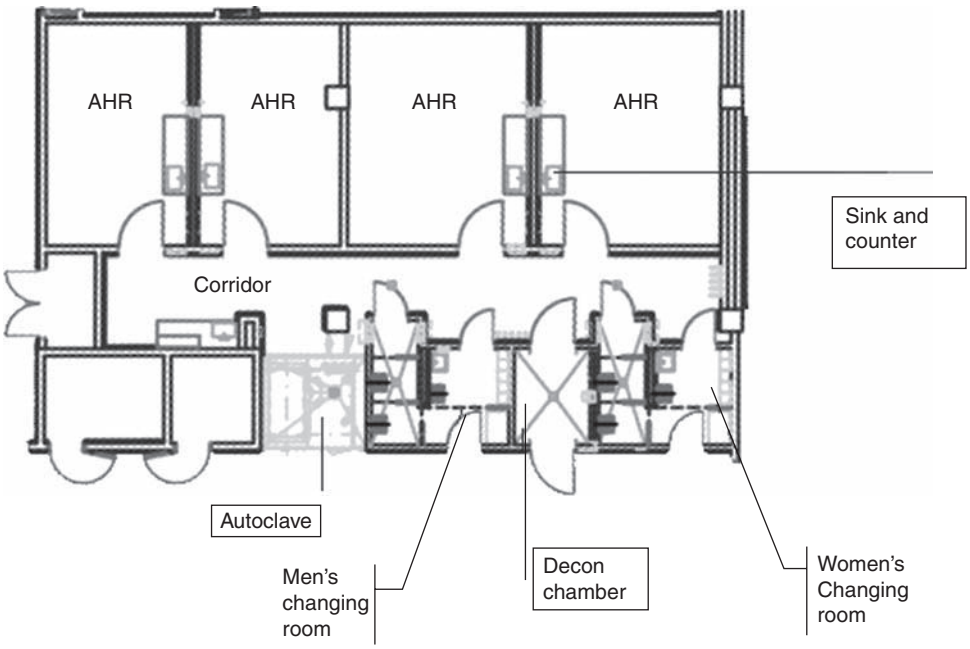

Fig. 26-6 A multi-room isolation area built to ABSL3 standards showing 4 animal holding rooms (AHR) with personnel entry through an airlock changing room design and allowing for progressively stronger differential air pressure gradients from the changing rooms to a central corridor and into each AHR.

Figure courtesy of Emory University, Atlanta, GA.

than the norm in the case where powerful animals, such as chimpanzees (Riddle *et al.*, 1982) or livestock, may be quarantined. Construction features that enable vermin exclusion cannot be over-emphasized. Importantly, utility service access should be from outside the quarantine area, typically in the interstitial space above the external corridor, for facilities management and physical plant maintenance personnel (Hessler *et al.*, 1999). For decontamination purposes, wall orifices should be provided for attachment of volatile hydrogen peroxide chambers or operation of fumigation equipment. Exhaust and supply ducts in the room(s), cubicle suite(s) and any anteroom(s) should be configured with dampers enabling the space to be sealed for fumigation. Sealing the anteroom enables the possibility to decontaminate large or complex pieces of equipment before removal into the uncontaminated corridor. Also useful may be a sleeve port for peracetic acid, chemical decontamination or pass-through dunk tanks (Hessler *et al.*, 1999).

Hand-washing sinks should be foot- or elbow operated (Hessler *et al.*, 1999; Rahija, 1999), and installed adjacent to any exit doors. A double-door pass-through autoclave, wall- or floor-mounted, should be present (Rehg and Toth, 1999; Rahija, 1999) and most ideally located on a wall connecting animal housing space with the anteroom. The capacity of the autoclave should be large enough to accommodate the throughput for a day's activity in one load or as few loads as possible. It may be advantageous to have a pass-through portal, separate from the pathway used by personnel, for the transfer of small animals and some supplies into the quarantine area, and decontaminated items out of the anteroom to the corridor.

Areas used for quarantine should have ample GFIC outlets and electrical power supply to simultaneously accommodate all powered equipment, including IVC, stationary biosafety cabinets, portable cage-change stations and other transiently used devices (e.g., electronic scales, computers, hot bead sterilizers, etc.). These should be connected to an emergency power source ensuring maintenance of at least air exhaust, nominal lighting and all electrical outlets. Optimally, both air-heating and -cooling should be on back-up power. Given the breadth of species that might be contained within the resource over time, full spectrum lighting should be provided (Ruys, 1991).

The most important concept related to the mechanical system is for air to be supplied and exhausted such that the quarantine space is maintained under negative differential air pressure relative to other areas (Kaufmann and Anderson, 1978; Rehg and Toth, 1998; Hessler *et al.*, 1999). In essence, air should flow in a gradient from areas of least risk into that of the greatest hazard (quarantine). This includes supply and exhaust ventilation down to the level of individual cubicles (Hessler *et al.*, 1999). To ensure that the differential air pressure remains progressively negative and properly balanced with respect to anterooms, corridors and other adjacencies, circulation should be regularly monitored with alarmed sensors. As a redundant failsafe, differential air-flow monitoring devices should be installed for local, visual monitoring of proper air-flow direction by technicians and other personnel in the area. This can be done using magnehelic pressure gauges or balum devices (e.g., a ping pong ball in a tube), or by affixing inexpensive flexible plastic strips at the door ventilation grill. To prevent abnormal relative air pressures in the case of a fan failure and reduce the possibility of contaminated air reaching the clean areas of the animal facility, a mechanism should be in place to cut off supply air by closing dampers or turning off appropriate fans. Likewise, to avert retrograde flow

of potentially contaminated air, supply-duct dampers should also close automatically when air supply is interrupted. Air turnover rates should range from 12 to 20 air changes per hour (ACH) for rooms (Kaufmann and Anderson, 1978; Hessler *et al*., 1999) and up to 35 ACH for cubicles (Hessler *et al*., 1999) in order to dilute and remove any micro-organisms suspended in the air in the quarantine environment. Design should allow for air-supply and exhaust ducts to be situated in light of computational flow dynamics, in order to promote the best air circulation for the space and to minimize unventilated "dead" pockets of air (Hessler *et al*., 1999). Air effluent from the quarantine area should not be recirculated, and air exhausted to the outdoors should not be discharged near air-intake ducts or elevator shafts. Finally, the principle of redundancy should be applied in the form of dual fan and filter systems along with emergency power supply.

Plumbing requirements are dependent upon the species housed and sanitation system used, except that generally an automated water delivery system for large animals should be designed into the area. For maximal flexibility, it makes sense to equip the facility with drains and cap them when not in use, such as for rodent quarantine. When in use, however, traps in floor drains should allow for the continuous presence of water or liquid disinfectant. Wastes should be disposed of in a safe and sanitary manner that complies with federal, state and local codes and regulations. Feces, soiled contact bedding and liquid waste from quarantine ordinarily can be disposed via the sanitary sewer system or incineration, or disposal by a licensed contractor. If waste is deemed to be of high hazard, however, it should be collected and rendered safe by appropriate means prior to removal from the facility. Where liquid waste presents extreme hazard, provision should be made for bulk collection and disinfection in heat-treatment tanks prior to discharge into the sewer system (Hessler *et al*., 1999).

With non-human primates and large animals, a fundamental consideration impacting design is the sanitation program and, in particular, whether it will be a so-called wet or dry system. Regarding the former, feces and urine collect in pan beneath cage or on the floor under a suspended expanded metal grid floor, and are periodically rinsed manually or automatically into a common drain. Where detergents and/or disinfectants are added to water for spray-rinsing, chemical burns or intoxication are risks if done overzealously (Kelley and Hall, 2002). Likewise, the splashing of water during wet cleaning procedures has been determined to be a risk factor for the transmission of tuberculosis (Ford *et al*., 1973) and, potentially, other agents (Kelley and Hall, 2002) in non-human primates. A variation of the basic wet system is the wet vacuum system, where the excreta pan is filled with disinfectant at all times and periodically vacuumed, but this adds the potential risk of splashing or creation of aerosols. If wet sanitation systems are used and a grinder is not incorporated into the system, 6-inch diameter drains are necessary to accommodate the discharge of the waste, and hair and gas traps may be necessary. Likewise, all drains should have short runs to the main, or be steeply pitched (Manning *et al*., 1980). For these reasons, albeit largely theoretical and weakly empirical, some facilities are managed using the dry alternative. In this system, shavings, shredded corn cobs, plastic, treated paperboard or other equivalent materials are used to bed the excreta pan. The pans are removed and replaced with appropriate regularity, decontaminated if necessary, and dumped and washed in the cage-wash facility.

Where there may be multiple users or where security is particularly important (given that high traffic and non-compliant personnel are the most likely sources of contamination and containment failure), microprocessor-controlled security systems using personalized identification codes can be used to control and document entry (Hessler *et al*., 1999). Other types of personalized information that can be used to allow and document entry include fingerprints and retinal images. View ports in doors, two-way intercoms, dataport access, and phone jacks for fax and telephone should be considered. These reduce the level of traffic in and out, and the ability to transmit data electrically from within the quarantine area and into administrative or other areas eliminates the risk of taking contaminated hard copies into these areas. Installing doors with view ports enables persons in the corridor to check visually for personnel in the room without compromising biosecurity by opening a door.

Although not essential, a shower and locker room are desirable (Hessler *et al*., 1999). These may not be necessary or practical, however, because compliance in such circumstances may be variable and difficult to monitor. Additionally, the effective use of appropriate personal protective equipment (PPE), with or without a clothing change, may be sufficient in many cases.

VIII. CONCLUSION

The well-established quarantine measures for non-human primates and those that have re-emerged for rodents are still necessary today. While there may also be a need to contain other wild-caught or large animal species, the increased use and exchange of genetically engineered mutant mice especially demands rodent quarantine capabilities for the majority of research institutions. Apart from species-specific housing requirements, it is important to consider pathogens to be contained in terms of the route of transmission and degree of hazard to human and animal health. Animals obtained from commercial vendors, as opposed to other research institutions, may be less likely to harbor undesirable micro-organisms, often allowing them to be exempt from a quarantine program.

The ideal quarantine facility should be flexible enough to allow the use of multiple species and take into account the number and frequency of shipments expected. The more shipments and different species involved, the more subdivided the facility should be, through the use of multiple rooms,

cubicles, isolators, etc. At a minimum, ABSL2 design criteria should be used to enable the containment of pathogens at the room or cage level, while also preventing agent transmission via contaminated animal waste, fomites, and personnel.

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Section IV

Systems

Chapter 27

Introduction to Specifications: General Considerations and Division 1

James F. Riley, Mark E. Fitzgerald and Noel D.M. Lehner

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I. WHAT ARE SPECIFICATIONS?

Specifications are the words that describe all aspects of a building project. Conversely, drawings are all the things that cannot be described adequately with words. The drawings and the specifications are like a hand and glove: they must fit together to be effective.

Specifications can be daunting to individuals new to the construction process. They tend to be large documents (frequently several hundred pages long), full of the technical jargon of architects, engineers and contractors.

Specifications describe how the project is administered, what products are provided, how they are installed, how they are tested, how building systems are engineered, how quality is safeguarded, and how the project is to be closed-out and finished.

II. WHY IS IT IMPORTANT TO READ, UNDERSTAND AND AGREE WITH THEM?

It is easy to focus on the drawings when planning and designing an animal research facility. However, it is very important to spend a significant amount of time on the specifications.

Specifications contain a great deal of critical information, such as:

1. Final finishes for walls, floors and ceilings
2. Equipment selections, options and accessories

3. Engineering system performance criteria
4. Quality assurance procedures
5. Product substitution options
6. Construction sequences that safeguard quality
7. Scheduling and safeguards for renovations within an occupied facility.

The facility director and veterinary professional should know all aspects of all elements of the building that will affect their ability to provide a quality operational environment. While it is good to trust the architect, engineer and contractor, it is better to verify critical decisions personally. You will be living with those decisions for a long time. The specifications are crucial to knowing and verifying many of the critical decisions of the project.

When a conflict arises between the drawings and the specifications, it is generally held that the specifications overrule drawings. This would not necessarily be true if the conflict were tried in a court of law. In court, specifications and drawings are supposed to be viewed with relatively equal weight. However, most conflicts do not go to court for resolution; they are negotiated between the contractor and the owner. It that forum, the most specific information overrules the more general. Therefore, specifications overrule drawings in most instances.

For this reason, the veterinary team members must know the specifications inside and out. They must agree with the choices of brand, make, model, style, color, options, accessories, operations and all other aspects of the products and systems specified. Making changes after the project has been bid is not a viable or cost-effective option.

III. HOW SPECIFICATIONS ARE ORGANIZED

Most firms in the United States adhere to the guidelines of the Construction Specification Institute (CSI). This publishes numerous documents to assist architects and engineers in organizing the huge volume of information that must be included in any construction project.

A. CSI Divisions

Historically, the CSI has recommended breaking specifications into 16 divisions of work as follows:

Division 1: General Requirements
Division 2: Sitework
Division 3: Concrete
Division 4: Masonry
Division 5: Metals
Division 6: Wood, Plastics and Composites
Division 7: Thermal & Moisture Protection
Division 8: Doors & Windows
Division 9: Finishes
Division 10: Specialties
Division 11: Equipment
Division 12: Furnishings
Division 13: Special Construction
Division 14: Conveying Systems
Division 15: Mechanical
Division 16: Electrical

B. Changes in 2004

In 2004, the CSI introduced a major change to the 16-division format. It changed the number of divisions from 16 to 48, and also changed the numbering system for the specification sections within the divisions from five digits to six digits. The reorganization created several new subgroups: Facility Services Subgroup (Divisions 21 to 28), Site and Infrastructure Subgroup (Divisions 31 to 35), and Process Equipment Subgroup (Divisions 40 to 48).

For the design and construction of research animal facilities, the CSI changes are relatively minor.

1. Division 2 (formerly Sitework) is now Existing Conditions. Sitework has been moved to the Site and Infrastructure Subgroup, and broken into five separate divisions:
   a. Division 31: Earthwork
   b. Division 32: Exterior Improvements
   c. Division 33: Utilities
   d. Division 34: Transportation
   e. Division 35: Waterway and Marine Construction.
2. Divisions 15 and 16 (formerly Mechanical and Electrical) are no longer used. The Fire Suppression systems that were in Division 13 have been merged with Mechanical and Electrical systems and are now contained within the Facilities Services Subgroup in seven separate divisions:
   a. Division 21: Fire Suppression
   b. Division 22: Plumbing
   c. Division 23: Heating Ventilating and Air Conditioning
   d. Division 24: Not used (Reserved)
   e. Division 25: Integrated Automation
   f. Division 26: Electrical
   g. Division 27: Communications
   h. Division 28: Electronic Safety and Security.

As of this work, the new system has not been widely adopted by architects and engineers. It will most likely take years for the new system to be adopted, as most construction projects span multiple years.

Within each division are the individual specification sections. It is not uncommon for animal research facility projects to have in excess of 150 specification sections. This may seem a daunting number to read and know, but many of the sections are for generic materials and methods. The authors of this chapter and

the ones that follow will elaborate on those specification sections that are most important to the process of building a quality animal research facility.

IV. HOW SPECIFICATIONS ARE STRUCTURED

Most specification sections are structured in a three-part format. These can be thought of as subchapters to the specification sections.

- Part 1: General
- Part 2: Products
- Part 3: Execution.

A. Part 1: General

This part deals with administrative and procedural items relating to the specified products. Part 1 will normally include the following.

1. Summary: a quick list of what the specification section covers.
2. References: a list of referenced standards that relate to the product or its performance in specific tests.
3. Submittals: a list of what the contractor must submit for review by the architect, engineer or owner for this specification section. This may include product data, sample parts and assemblies, shop drawings, test data to prove compliance with referenced standards, as well as final closeout submittals.
4. Quality Assurance: this subsection will vary widely with application to the various specification sections. It is frequently used as an area to speak to the requirements of both the manufacturer's qualifications as well as that of the installer. This subsection can also be used to describe the requirements for mock-ups. Quality assurance can also be used to describe required test certifications and regulatory compliances.
5. Delivery, Storage and Handling: generally this is an area used to describe cautions associated with protection of the products or equipment specified in the section during the course of delivery, storage before installation and all handling during the construction.
6. Project & Site Conditions: for many specified items, certain environmental conditions must exist at the site prior to delivery if they are not to be damaged. Temperature and humidity limits are often specified. Other variables may include weather, ventilation, illumination, dust control, and wet operations. Many specified items must be carefully coordinated with accurate measurements of the actual construction to assure the best final fit and finish. This subsection is also used to address the need for field measurement of new construction and existing conditions with renovation projects.
7. Sequencing & Scheduling: this subsection is for noting any unusual sequencing or scheduling requirement. The contractor has the responsibility to control sequence and schedule for the project and usually the specifications do not dictate means and methods, so this subsection is only applicable for unusual situations and special cautions.
8. Warranty: this is a description of any warranty criteria beyond the basic contractor's warranty (which is usually 12 months). It is important to be clear about when the warranty period begins. There may be a significant difference between the date of substantial completion and the date of occupancy.
9. Maintenance: this is usually a list of extra materials or maintenance materials to be supplied to the owner at the end of the project. These items may include things like a percentage of flooring or ceiling tile, or specific quantities of things like paint (1 gallon of each type used on the project, etc.). These items are sometimes referred to as "attic stock." Most often these maintenance materials are associated with final finishes, things that may be subject to unusual wear and tear or things that may be difficult to match at a later date.

B. Part 2: Products

This part describes everything about the products that are the focus of the specification section. As with Part 1, there is a typical order and listing of subsections.

1. Manufacturers: typically a list of approved manufacturers that are capable of providing the products specified. Often this subsection will name one manufacturer as the "basis of design" and then name other manufacturers that may also compete, provided that they meet the criteria established by the named product.
2. Existing products: sometimes the project needs to match equipment or systems that already exist such as with renovation projects. The need to match existing conditions must fully explain what characteristics are critical to "match." By default, any characteristic omitted is not critical to the matching process.
3. Materials: in many cases, the specific characteristics of the materials of construction are critical to the performance of the product. This section can be used to address chemical resistance of finishes, strength of various materials, recycled content of materials, outgas properties of finishes, gauges of metals, thickness of wood members, species of wood, or it may list various raw materials with test criteria. The section is applied in a wide variety of ways over the many specification sections.

4. Manufactured Units: this subsection details all the information about manufactured products that are incorporated into the project. These can be standard catalog items described by make, model number and features. If a particular manufactured item is the "basis of design," this specification subsection must detail all the characteristics that form that basis. Any characteristic not mentioned is considered as not critical to the matching process. At the same time, care should be taken in making the list of criteria such that you do not preempt competition between vendors.
5. Equipment: like manufactured items, equipment that is specified should include make, model number and features. Any specific performance criteria should be listed. If there is a basis of design, list all the characteristics and performance features that constitute the basis. Any characteristic not mentioned is considered as not critical to the matching process. This can be especially critical with equipment that must fit within existing dimensions (renovations) or have specific height or weight characteristics. Cage washers and large pit-mounted sterilizers are examples that have significant differences from vendor to vendor.
6. Components: sometimes the specification lists all the components of an assembly as separate items. The same requirements apply as with manufactured units or equipment. It is important to provide adequate information about the component performance or features, so that the correct component is selected.
7. Accessories: many products are assemblies of basic products with a variety of add-on accessories. This is especially true of cage-processing equipment, sterilizers, operating room equipment, laboratory equipment and casework. Accessories can make the difference in proper performance of many products. This is an area to focus on in the design process.
8. Mixes: with some products, the formulation or chemical mix is the defining characteristic. For those products, the specification should describe the mix proportions and composition as well as procedures critical to achieving a proper mix.
9. Fabrication: specification writers use this subsection to describe any issues concerning the fabrication of products. These can be shop-specific procedures, methods or tolerances that are critical to the proper fabrication of the product.
10. Finishes: this subsection is used to describe all aspects of the product finish. It may include pre-finish product preparation, type of finish, number and type of finish coats, cure times and environmental requirements for the finishing process.
11. Source Quality Control: this subsection is used to describe any requirement for quality control that involves source control. A particular example of this is a requirement that the manufacturer/provider of chemical fume hoods on a project be the same manufacturer/provider of the laboratory casework. This assures that the coordination of two critical items is under the quality control of a single source. Other examples include grouping cage-wash equipment with sterilizers, or making sure that all the biological safety cabinets are from one manufacturer. This can simplify service agreement management.

C. Part 3: Execution

This part describes the criteria for installing the product into the project context. As with Parts 1 and 2, there is a typical order and listing of subsections.

1. Examination or Inspection: this subsection states the specific requirements of the construction site prior to installation of the product. This is also a place to tell the installers that it is their responsibility to examine or inspect the area where their products are to be installed, and to not install the products until the site is prepared properly.
2. Preparation: many projects require special focus on coordination between trades or product protection as part of the site preparation for the product installation. This subsection articulates these items. An example is to require that all utilities be roughed in prior to installing a piece of equipment. This avoids possible damage to the new equipment.
3. Installation: this section will vary widely in the level of detail applied. Some products require minimal installation notation and may simply be noted as "install per manufacturer's requirements." If this is the case, a copy of those requirements should be part of the submittals made in Part 1 so that they can be reviewed prior to installation. Other products will require detailed installation requirements. These requirements should be clearly detailed, including any tolerances, special techniques, precautions, sequences, curing times, coordination between trades, workmanship issues, choice of fasteners, applications of adhesives and joinery finishes.
4. Repair and Restoration: especially with renovation projects and work adjacent to existing finishes, the specifications should provide details about the requirements for repair and restoration of finishes and systems.
5. Quality Control: this subsection is used to detail any on-site forms of quality control associated with the installation of the specified product. Items regularly seen with Animal Research Facilities include certification testing of fume hoods, biological safety cabinets, mortuary equipment, cold rooms, cage-washing equipment, sterilizers and other performance based equipment and systems.
6. Adjusting: some pieces of equipment require adjusting after an initial break-in period. This is the subsection to note the requirement to provide any required post start up adjustments prior to building occupancy.

7. Cleaning: construction sites are dirty – they are actually very dirty. As a result, substantial cleaning is needed at the end of a project prior to occupancy. This subsection can be very useful in enforcing a clear and specific level of cleaning that is expected prior to occupancy. It should be coordinated with any cleaning specification listed in Division 1. When spelling out the expectations for cleaning, remember that contractors have a different view of what "clean" really means. To them, "clean" is what a contract cleaning company will provide for the lowest possible price. Unless the specification is very clear, it is likely that the cleaning reality will fall short of expectations.
8. Demonstration: with complex equipment and building systems, it is a very good idea to require the product or system provider to demonstrate the proper use of the product to the building staff. These demonstrations are frequently videotaped or recorded so that future staff can be trained. This subsection is used to describe the expected performance of the trainers, the training materials provided, the recording format, and the scope of the training. Topics that are regularly included for equipment and systems are start-up and shut-down, emergency situations, preventative maintenance requirements, overview of the Operation and Maintenance Manuals, explanation of controls, discussion of spare parts, filter changes, and all the aspects of normal day-to-day use of the product or system.
9. Protection: it is necessary to protect the product until the owner occupies the building. For items like casework and laboratory equipment, protection is critical and must be well articulated in this section. Detailed protection requirements give the architect or engineer the ability to enforce protection of the products. One good item to include in this section is to state that the architect/engineer shall be the sole judge of repair-or-replace options with the product.

V. HOW SPECIFICATIONS ARE WRITTEN

Specifications are written using two basic styles. Most specification manuals use both of these styles as appropriate to the items being specified.

A. Performance-Based Specifications

With performance-based specifications, the focus is on the end result; what performance is desired from the product being specified? This allows the contractor to search out a wide variety of products that will meet the performance and choose ones based on performance and cost. Many building materials can be procured for the best value with this style of specification: concrete, concrete masonry units, bricks, pipe materials, wiring, hollow metal door and window frames, gypsum wall board, heavy steel, light-gauge steel studs, ductwork, insulation materials, and a long list of other generic items and materials.

B. Prescriptive or Proprietary-Style Specifications

When it comes to final finishes, building controls, critical equipment, and key engineering systems, performance-based specifications should not be used. For these items, prescriptive or proprietary-style specifications should be utilized. Proprietary specifications name acceptable brands of products or acceptable suppliers. To get the best value for the product, maintaining a healthy competitive range is suggested. The general rule is to have at least three providers of acceptable products for each specified item or system.

When three or more acceptable brands are not identified, architects will use a method that opens the otherwise proprietary specification to more options. This is called the "or equal" option. The specification names two items by brand and model number, and the third item is simply listed as "other manufacturer as determined to be equal to the named products." The trick here is to be more specific than just "or equal." The specification should name who determines whether something is equal or not – so a better way to put this would be: "Other manufacturers whose products are equal to the named products as determined by the Architect/Engineer." It should not be the contractor who determines what constitutes "equal" to the brands already selected.

As a member of the owners' team on the project, it is always advised that the operator knows all the products being specified. This includes the primary product or basis of design, as well as the other brands mentioned. All must be acceptable to the long-term operator of the facility. Do not be shy about voicing concerns about any product. Remember; decisions will have to be lived with every day once the facility is built.

VI. DIVISION 1 SPECIFICATIONS: GENERAL REQUIREMENTS

Division 1 is all about the General Requirements of the project. The section includes everything administrative about the project. Since Division 1 is not about products, it is about administrative process, Part 2 of the standard specification format is not always utilized.

Typical Division 1 specifications include:

01100: Summary of Work
01200: Price and Payment Procedures
01300: Administrative Requirements
01400: Quality Requirements
01500: Temporary Facilities and Controls

01600: Product Requirements
01700: Execution and Closeout Requirements
01800: Performance Requirements
01900: Life Cycle Activities

Each of these specifications may be further broken down into multiple specifications using numbering within the 100 number block.

There are a number of Division 1 specifications that the owner/operator must read closely. These sections are listed below by individual specification section number. On some jobs these sections will be rolled up into the broader heading listed above.

01140: Work Restrictions. This section details restrictions placed on the contractor for work time or limits of access. When the project involves a renovation of an existing operating facility, close attention should be paid to this section to be sure it works with ongoing operations. When the project is an addition or a very closely adjacent site, be sure that the contractor's operation is coordinated with sensitive activities within the existing facility.

01210: Allowances. This is a list of blocks of money for parts of the project that may lack good definition. This category should not include any laboratory equipment, cage-wash equipment, sterilizers, final finishes or critical engineering systems. The only items that should be here are allowances for unforeseen conditions, like removing underground rock.

01230: Alternates. This section is for pricing and possibly accepting something in lieu of that which is specified. An alternate might be doing a partial scope reduction to save money if the budget is tight – an example would be providing two wall shelves in lieu of the three shown in a selected set of rooms. Make sure that there is agreement regarding any item that is in the alternate list. When projects come in over budget on bid day, the alternate list is the first place the owner and contractor look for money savings.

01400: Quality Requirements. This is the section where requirements for full-system mock-ups will occur. For animal research facilities, mock-ups are essential to set the quality of the installation of many of the final finishes. Special attention should be paid to the scope of the mock-ups. One suggestion is to mock-up the wall finishes on sample walls and repeat the procedure until the finish is acceptable, and then do a room-scale mock-up with floors and walls and ceiling finishes. It is important that all objects that the finishes will touch (like doorframes, plumbing pipe, sprinklers, etc.) are in the room; that way, the mock-up is for all aspects of a typical room.

01630: Product Substitution Procedures. As a member of the owner's team for a research animal facility, it is important to know when the contractor is proposing to substitute anything in lieu of what has been specified. Frequently, the research veterinary professional is not the one representing the owner on a daily basis and can be somewhat removed from the process at times. Substitutions are a time when the operator needs to be part of the process. Within this specification section, it is possible to designate who is authorized to approve substitutions and who is not. For all critical animal-care equipment, floor and wall finishes, security and building controls, the research veterinary professionals must be made part of the process of approvals for any substitutions.

01740: Cleaning. This section details the overall requirements for cleaning during construction and prior to occupancy. Most specifications do not address cleaning adequately. This section must be read and challenged until it meets the operator's expectations for move in day. It is important to be specific: glass cleaned, mirrors polished, light lenses cleaned, stainless-steel finishes polished, all construction labels and marks removed, all casework drawers vacuumed clean, all floor drains cleaned (including baskets), all filter grille filters changed, etc. Each room and each item must be considered, and its expected cleanliness articulated in the specification.

01760: Protecting Installed Construction. The old saying goes "you break it, you buy it." However, this does not seem to apply to construction workers. Most specifications are not very strong when it comes to requiring protection of the work from damage during construction. This is a specification section that needs to be specific to be enforceable and clear in the consequence of non-compliance. Suggestions include: prohibit walking on or using casework or lab equipment as a work platform; make the architect/engineer the sole person to determine the option of repair or replace; require rooms to be locked down once final finishes are installed; and use full coverage hardboard to protect floors and walls (especially for epoxy or MMA flooring).

01900: Life Cycle Activities. This section is where commissioning activities are detailed. This is an area of critical importance to any research animal facility. Each critical piece of equipment or building system should be listed as part of the commissioning plan.

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Chapter 28

Structure

Mark A. Corey, John O. Bauch, Tom E. Gatzke and Robert E. Faith

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I. STRUCTURE

Structural design of a vivarium facility is a unique engineering challenge. No two vivaria are identical, but all include many common elements combined in different ways. A successful design requires prudent material selection and thoughtful detailing of individual building elements. To create a better understanding of the elements involved, and to understand the options within each, they will be covered individually within this chapter.

A. Building Shell and Frame

The shell and frame of the building is designed under the same national model building codes as any other type of structure. In the United States that normally means the International Building Code (IBC), with whatever specific enhancements local or state code officials may require. It should be noted that model building codes represent the "code minimum" design standards that must be met. It is not unprecedented that a vivarium owner would desire a higher level of building performance than afforded by the model building code, and would elect to pursue voluntary design enhancements or upgrades that exceed the code minimum requirements for structural systems. For example:

1. Facilities that are located in moderate to high seismic risk zones may want to consider use of the design procedure published by the Structural Engineers Association of California (SEAOC). This procedure is called *Performance Based Seismic Engineering*.

Seismic design procedures prescribed in model building codes are based on the objective of maintaining life-safety. Their primary objective is to protect human lives so that evacuation can be accomplished after a severe but relatively infrequent earthquake. Life-safety design provisions do not address post-earthquake design objectives such as: (1) the extent to which the facility will remain operational; (2) whether the facility be immediately reoccupied; and (3) the degree of functionality of non-structural systems such as architectural, mechanical, electrical and plumbing systems. This is particularly true for more frequent, less severe earthquakes. Thus, a building designed to meet only the life-safety code requirements may not be operational or accessible for re-entry after a seismic event.

In the case of vivarium facilities, the contents of the building represent a significant investment by the owner and often rely on essential services such as temperature control, food, water and ventilation. If a laboratory or vivarium facility is not designed for immediate occupancy after an earthquake, there is a much higher probability that research data and animal models will be lost because caretakers may not be allowed to re-enter the building. The "code minimum" design procedures in model building codes cannot achieve structural and non-structural system performance outcomes with the same level of reliability as the enhanced design procedures used in Performance Based Seismic Engineering.

2. The model building codes often require that impact-resistant cladding be used in facility design to protect against damage from windborne debris in coastal high wind zones. Facilities that are located adjacent to these zones may not be obligated to meet the code requirements, but may want to consider voluntary hardening of certain portions of the shell to prevent loss of investment in research data and animal models.
3. Vibrations on floors supporting animal cages, or on floors above animal rooms, can be disruptive to animals. Although no standard or code vibration criterion is available for this type of environment, it is recommended that floor vibratory accelerations be limited to 0.2%g and vibratory velocities to 4,000 micro-inches per second based on a moderate walking-speed forcing function. The project design team should avoid locating sources of vibration (such as loading docks, reciprocating equipment and fork-lift routes) in close proximity to animal spaces.

It should also be noted that care needs to be taken in choosing the code-defined building occupancy category due to the sensitive nature of the work being done in this type of facility and its potential hazards to the public. The project team for a vivarium facility should determine, at the outset of the design process, what level of facility performance is desired. Once the appropriate code occupancy category and design parameters are selected, design of the shell and frame can begin.

Shell and frame material selection can involve steel, concrete, masonry or pre-cast concrete systems. Economics, strengths, span considerations and the overall requirements of the complete facility all affect the choice of the basic building-frame materials. Specific requirements for the vivarium elements themselves may also influence this decision, but often the vivarium is an isolated box within a box. It will not greatly influence the shell design other than coordination of the column grid with animal room partition layouts. An exception to this is an animal facility, with floor trench drains, located on an elevated floor. This type of facility will likely favor the selection of a cast-in-place concrete frame to facilitate sloped floors, depressed trench drains, and waterproofing details.

B. Slab-on-Grade

The most important issue with the slab-on-grade design is the control of random cracking in the floor slab. Slab cracking can be detrimental to floor finish systems, resulting in potential sanitation and maintenance problems. Slab cracking can be controlled in several ways, including the use low shrinkage concrete mix designs, shrinkage control admixtures, larger percentages of slab-reinforcing steel, and control joint spacing. Shrinkage control admixtures can be used along with mix design modifications and testing.

Slab reinforcing is also effective in preventing cracking and in limiting crack widths if they do occur. Many papers, codes and industry design publications list methods to define the appropriate amount of slab reinforcing. The variables within these recommendations are slab thickness, control joint spacing, and the sub-grade friction coefficient. Practical experience has shown that many of these methods result in relatively low reinforcing values, stated as a percentage of the gross concrete slab cross-sectional area. It may be advisable to use higher minimum reinforcing percentages.

Control joint spacing is one of the most effective ways to control slab-on-grade cracking. However, control joints themselves are not usually desirable within the animal or lab rooms, since both control joints and construction joints can be detrimental to performance of floor finish systems. Locations that are potentially acceptable are under walls, or at the interface of a wall that passes through the slab-on-grade. This results in control joint spacing which matches the boundary of the animal or lab rooms.

Floor finishes require collaboration between the structural designer and the entire design team. Many floor finish systems that are used in animal facilities are very intolerant of moisture vapor transmission through the slab-on-grade. The geotechnical consultant, the structural engineer and the architect should devise an appropriate vapor barrier solution below the slab per the conditions that exist on the site. A successful solution will prevent transmission of sub-grade moisture through the

slab-on-grade. The material used for curing of the concrete slab must be taken into consideration with the floor finish as well. Most resinous floor finishes require the slab-on-grade to be prepared by "shot blasting," which removes the curing compound and roughens the surface. This will allow the resinous floor to bond properly to the slab. Floor textures are also often employed, especially in large animal facilities. A "stamped" texture system can be applied to the top surface of the slab in areas where hoofed animals will be required to walk.

II. INTERIOR CONSTRUCTION

A. Partitions

Partitions in vivarium facilities are generally constructed from either concrete masonry units (CMU) or cold-formed metal framing systems (CFMF).

CMU walls are the most common type of wall found in animal facilities. They are durable, moisture-resistant and have desirable acoustic qualities. Interior wall partitions, per IBC, need to be designed for a 5 pound per square foot uniform lateral load. However, this load is relatively light, and designers should consider a higher design value. Large animal facilities for bovines, swine or equines need special consideration due to the size of the animals and the swinging gate load that is typically associated with these facilities.

The structural design of the wall is also dependent on the lateral support at the top of the wall. Several conditions may exist. The wall can extend full height to the bottom of a floor system above where it is laterally braced, or it may terminate just above the ceiling line and not be tied to any floor plate. Given the amount of ductwork above the animal rooms, it is often not desirable to run the partitions up to the deck above. If the wall is not supported at the top, it will need additional bracing to provide lateral support.

In all CMU designs, it is critical to provide sufficient reinforcing to address both strength and ductility considerations. At a minimum, reinforced bond beams are recommended at the top of the walls, horizontal wire joint reinforcing at 16" vertical spacing and # 4 vertical rebar at 48" horizontal spacing. Vertical reinforcing should also be provided at all door and window jambs and corners.

The base detail for CMU walls can be addressed by either extending the wall through the slab-on-grade and supporting it on an independent wall footing or by supporting the wall on top of the slab-on-grade itself. The independent footing detail is preferred if the CMU wall is load-supporting. This detail has the added advantage of creating a slab control joint at the face of the wall that helps control concrete shrinkage. If the wall is supported on the slab-on-grade, the slab will need to be designed to carry any supported loads and the self-weight of the wall. This latter scenario may require a thickened and reinforced slab below the wall.

CFMF walls have the same top support issues that CMU walls have. They also can be extended to the structure above or terminate just above the ceiling line. If stopped short, they also require kickers or some other means of support at the top to provide stability. Although not as durable as CMU, an advantage to this type of wall is that utilities, including floor-level air returns, can more readily be placed within the wall thickness. Although still disruptive during renovation, these types of partitions are more flexible, as they are easier to remove, modify and install. The appropriate surface material must be chosen for the function of the room. Several types of board materials are available for consideration. These consist of abuse-resistant, fiberglass-reinforced or moisture-resistant gypsum boards – in some cases, all three combined. In addition, there are cement board materials and fiberglass-reinforced plastic materials that can be applied to the CFMF studs in the case of a wet environment. Cement board products need special considerations for finishing, given their rough surface texture. In all cases, the function of the room should be taken into account when choosing the partition material and finish.

The use of wood materials in a vivarium is discouraged, since they can promote the growth of contaminants that could affect the animals and research. Bracing, blocking and supports in CFMF partitions should be metal material in lieu of wood.

B. Floor/Ceiling Structure

The structural design of the floor system with an applied or suspended ceiling is straightforward, since only the additional weight of the ceiling material need be accounted for in the design of the floor structure. Walkable ceiling assemblies need to span the width of the animal rooms and support a catwalk or other walkable surface along with the weight of the ceiling assembly. These systems are often constructed with materials such as structural steel, CFMF joists, pre-cast hollow-core plank, metal deck and plywood.

III. SEALING THE ROOM ENVELOPE

All penetrations in partitions will need to be sealed to control airflow and vermin. This includes both masonry and CFMF partitions. Masonry walls are generally sealed at the top, but CFMF walls are open at the top. This means that the perimeter of the room at the partition is really the "barrier" for the facility. All openings for fixtures, diffusers, lights and miscellaneous devices must be sealed airtight. In addition, CFMF partitions often have mineral-wool insulation installed in the cavity to reduce noise transmission between rooms. The

phase of construction when wall partitions are being installed and before they are capped is a good time to treat the hollow spaces in the wall and other structures with silica dust. Silica dust is a non-toxic, non-corrosive insecticide that will greatly reduce the chance for these spaces to serve as harborage sites for insects as long as the dust stays dry, which should be for the life of the building.

IV. SUMMARY

This chapter has discussed the structural aspects of the animal facility. Subjects covered include the building shell and frame, slab on grade, and interior construction. Information presented includes national model building codes, local codes, seismic design issues, and pluses and minuses of slab-on-grade construction. The interior construction sections include comments on partitions, floor and ceiling structure, and sealing the room envelope.

Chapter 29

Doors and Hardware: Practical Choices

J. Erik Mollo-Christensen

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Door and hardware selection for vivaria is a basic but important part of the design of an animal facility, as it affects security, operational control and physical long-term durability. Appropriate selection and specification requires detailed knowledge of vivarium operations, as well as door, frame and hardware materials, but is based on a practical approach and common sense that veterinarians and animal facility managers can apply successfully.

Engaging an experienced architect or vivarium planner is a necessary part of the design of new and extensively renovated facilities, but, even before working with these consultants, veterinarians and vivarium managers can develop a basic understanding of the principles and components that will facilitate the design process. The daily activities within any vivarium include successful examples of door and hardware that work, provide proper access control, and offer enough durability to minimize maintenance. In addition, the lessons learned from a typical accreditation inspection inevitably include door and hardware items, such as chipped paint at unprotected door and frame locations, rusted ferrous components, damaged unprotected hardware, and inappropriate locking or lack of locking. All of these observations, gained by simply walking around a vivarium, can be the basis for planning a new facility.

Door and hardware specification and installation is a very detailed, specific and sometimes arcane discipline, with a level of complexity that can be intimidating even to experienced technical individuals in other fields. In spite of this, the basic knowledge required to describe functional needs is straightforward and tangible based on daily experience. Terminology within the world of doors and hardware is also arcane, but equally straightforward for basic items; this chapter will review the essentials.

I. FUNCTIONAL PLANNING

Planning for doors and hardware is integral to the basic architectural and space planning for a vivarium. The work flow and circulation for people, animals and materials is inherently controlled by doors, and animal health, separation of clean and soiled areas, and barriers/containment separations all rely on proper placement and selection of doors and hardware. As the research program is developed and the corresponding space program is quantified for various functions, such as housing, procedures, cage-washing, vivarium support, imaging and special testing, doors can be located to organize and separate each area and control circulation.

Specific planning principles for doors and hardware include the following:

- *Door width*: this should be 3'6" or 4'0", for clearance of transport and cage racks. Turning movements between room and corridor require more room if the corridor is not wide enough to orient racks perpendicular to the door.
- *Door height*: this should be 7'6" to 8"0" for clearance of cage racks, especially ventilated racks with blowers above. The dimension of suspended items such as door closers must be included in clear height calculations.
- *Door placement*: doors should be located to provide minimum side clearances required by the Americans with Disabilities Act (ADA): 12" on the push side, 1'6" on the pull side. The door swing also affects the room layout, including locations for movable and fixed items such as casework.
- *Proximity of actuating hardware*: for doors with automatic operators or sensors, actuating devices such as push paddles should be located at normal walking stride distance from the door after it has swung open.
- *Budget planning*: because of their typically larger size and greater number of hardware components than office or laboratory doors, vivarium doors need to be budgeted at 1.5−2 times the unit cost; in 2008 costs, this is typically a range of $1,500−$2,000 per opening. Doors with automatic operators, card readers, or biometric devices can cost considerably more. In addition, with doors and hardware there is a direct and linear relationship between cost and performance, and a higher initial investment almost always produces a lower lifecycle cost, so planning for adequate door and hardware budgets at the early project stages is essential.

Security is an essential part of functional planning, and identifying door openings that will need security devices is important at the early planning stage. During initial planning, specific device selection is not needed, but decisions about access control or monitoring are necessary.

- *Access control*: this term refers to the control of entry and/or exit through a door opening; this is usually accomplished by a combination of a control device such as a key or card reader, and a locking device, which can be mechanical or electrical.
- *Access monitoring*: this refers to the indication and/or recording of an access event, usually by means of a magnetic switch within the doorframe that sends a signal to a central system when a door is opened, or by means of a closed circuit television (CCTV) camera that is either recorded or observed by a guard.

Building code requirements for egress and accessibility must also be considered with early planning. Desired security and control within vivaria sometimes conflict with building code requirements, especially with respect to controlled exiting. The basic principles and requirements are as follows:

- *Egress*: all rooms and spaces must provide free egress in the event of fire or other emergency, and the maximum travel distance to a fire-rated stairway or exterior exit is limited by code requirements.
- *Hardware*: all door hardware used for exiting a room must be readily operable with a single motion; this typically means that the lever must retract both a latch bolt and any locking mechanism. Two-step motions, such as retracting a dead bolt and then operating a lever, are prohibited.
- *Fail safe*: with few exceptions, all electrically-locked hardware such as card reader-controlled doors must default to an unlocked condition in the event of fire-alarm activation or power failure. This is a life-safety issue, but obviously presents some challenges for vivarium security, and must be carefully designed to be code compliant.
- *Delayed egress*: there are only a few instances where a delayed egress function may be used; this is typically a panic-bar type exit device that must be pushed and held continuously for 15−30 seconds before the lock releases. Codes also have a limit of only one such device in sequence in a single egress path, so their use must be carefully considered.

Accessibility and ADA compliance is an additional planning consideration that must be incorporated at early design stages. ADA is a federal law that overlays state and local building codes, and is a legal requirement for all facilities. Although many or most aspects of vivarium operation and management require individuals to be able-bodied as a legitimate work requirement, this may not be the case for supervisory or office positions, and with the growth in barrier facilities and the resulting presence of many investigators within the vivarium, ADA compliance and the provision of a minimum of one accessible route into every space becomes necessary. This affects not only the location, width and access clearance for doors, but also the selection of hardware. Levers rather than knobs are required, and the use of dead locks requires careful inclusion of ADA handles and pulls.

II. DOOR AND FRAME MATERIALS

Doors and frames in vivaria receive a great deal of wear and abuse during material movement and operations. Transport carts and cage racks are often heavy and bulky, and frequently taller and wider than the individual pushing them, which results in regular contact and impact with doors and frames. Frames often act as default corner guards in door openings, and the extent and variety of hardware devices, as well as sanitation concerns, suggest robust and durable materials be used. In addition, as noted above, the relationship between cost and performance is direct, and more expensive components and materials usually justify their higher initial cost with a lower long-term cost for maintenance and operation.

Hollow metal doors and frames are the most common types used in commercial buildings; they are produced as commodities within predictable and reliable construction and dimensional standards, and manufacturers are highly competitive so costs are reasonable. Steel is the most common metal used, and is typically painted. Doors and frames using this method are formed from sheet steel and welded; this produces seams on the edges of doors that need to be ground smooth or filled for easy cleaning. Some of the specific features of hollow metal doors and frames are as follows:

- *Galvanized coating*: this reduces corrosion from washing and caustic cleaning/decontamination agents, accepts epoxy or enamel paint with appropriate primers, and is recommended for wet areas such as cage-washing.
- *Painting*: steel hollow metal must be painted; epoxy coatings are the most durable and resistant to moisture and cleaning agents.
- *Stainless steel*: the same manufacturing techniques can be used with stainless steel, usually Type 304 alloy, resulting in a self-protecting assembly that does not require painting.
- *Door construction*: closed tops and bottoms should be specified to eliminate pockets to trap contamination or harbor vermin.
- *Frame construction*: fully welded frames are preferable and considerably more rigid and durable than knock-down frames; also, the absence of seams reduces potential dirt and contamination.

Fiberglass-reinforced plastic (FRP) doors and frames are fabricated from an inert core coated with fiberglass cloth or fibers and plastic resin, resulting in a door with integral color not needing painting, and a highly impact- and cleaning-resistant smooth flush surface. These doors and frames are very durable, but have a higher initial cost than hollow metal; there are also fewer manufacturers of FRP doors.

Both doors and frames need to be fabricated (prepped) to receive the planned hardware; this is most easily performed in the factory, but some field modifications can be accommodated if necessary. This means the selection of specific hardware requirements must be completed before the doors and frames are ordered.

III. HARDWARE

Hardware can quickly become considerably complicated, and the range, nuance, and multi-dimensional variations in seemingly simple components can be intimidating. Specialized architects, hardware consultants and hardware subcontractors are good sources of detailed advice. This section will describe the essential aspects of the basic components.

A. Basic Terminology

- *Lockset*: this includes a mechanism mounted in the door that uses a handle (lever or doorknob) to operate a latch, and usually includes some locking function. The term *lockset* is used even if no actual locking is involved, although some refer to non-locking hardware as *latchsets*.
- *Latching*: this refers to the mechanical engagement of a latch that prevents a door from being pushed or pulled open.
- *Deadlock*: this is a lockset operated by a key only, with no lever or knob. Deadlocks are only used (and only permitted by building codes to be used) for unoccupied rooms or closets, which could be interpreted to include animal holding rooms. The life-safety aspect relates to the ability of a person to exit a room freely with a single motion.
- *Hinge*: hinges are generally available as *butt hinges* or *continuous* hinges; the former consists of a pair of plates 4"−5" long, with knuckles and often ball bearings; the latter is similar to a piano hinge. Hinges need to be sized to match the weight of the door and the frequency of use.
- *Strike*: strikes are the formed plates mounted on the frame that receive the *latchbolt*, a tapered piece projecting from the lockset. Strikes in vivaria should be specified with closed-strike boxes to prevent air infiltration from within the wall or frame.
- *Mortise lockset*: this is a lockset that has a rectangular case that is mortised into a recess in the edge of the door. This is the most durable type of lock and is recommended for vivarium use in high-traffic or high-frequency locations.
- *Cylindrical lockset*: this is a lockset that has a round case installed into a large (2 1/2"−3") hole in the door. These are typically seen in residential and commercial applications; they are available in heavy-duty versions, and are both less costly and less durable than mortise locksets.

- *Exit device*: commonly known as panic bars, exit devices are push-bar activated locksets typically used at exits in assembly occupancies, but are frequently used for convenience in vivaria for hands-free operation. These are usually mechanical, but can be interlocked with electrical and security devices.
- *Electric locks*: there are several varieties of electrically-operated locking devices. *Electric strikes* are the most common. These use an electromagnet to hold or release the strike mounted in the frame; the major disadvantage is that they usually fail safe and become unlatched in failure mode, which precludes their use in fire-rated doors that must remain latched. *Electromagnetic locks* are magnetic bars mounted at the door head; these have no moving parts and are extremely reliable, but provide no latching function and inherently fail unlocked. *Electric locksets* incorporate an electromagnetic locking function into the lockset itself, and allow the use of regular strikes and remain latched in failure mode.
- *Closer*: this is a hydraulic mechanical device that automatically closes a door, and is usually mounted at the head. It typically intrudes into the overhead clearance of the doorframe, so should be considered when door heights are set for moving materials and carts. Concealed closers are available, but are more costly and harder to access for maintenance.
- *Automatic operator*: this is a motorized overhead device that opens doors when activated by a push paddle, proximity sensor or card reader. Similar to automatic doors seen at retail store entrances, automatic operators open a door within a few seconds to allow hands-free passage.
- *Stops*: these are bumpers located on the wall or floor to prevent the door from damaging the wall. Floor-mounted types are more rigid but pose a cleaning challenge; wall-mounted stops in drywall partitions require solid wood internal blocking. A more costly but effective alternative is an *overhead stop*; this is a flat bar that slides along the top of the door (similar to closer arms) and limits the swing travel of the door.
- *Door hand*: this is terminology that describes the direction of swing of a door, and thus indicates on which side of the door and frame the lockset and other hardware is mounted. For planning purposes it is adequate to locate the door swing on a floor plan based on functional needs, and leave the designation of handing to the architects and hardware suppliers. Simplistically, a "right-hand door" has the hinges on the right side when seen from the corridor/entry side of the door, while a "left-hand door" would be the opposite.
- *Hardware grade*: there is a wide range of grades and qualities of hardware available, but for vivaria and other heavy-duty use applications it is recommended that ANSI/BHMA Grade 1 [A156.13, Series 1000, Grade 1 Operational] be specified. The merged reference standards of the American National Standards Institute (ANSI) and the Builder's Hardware Manufacturer's Association (BHMA) provide a definitive requirement, rather than general terms such as "medium-duty" or "heavy-duty."

B. Functional Planning

Functional planning of hardware needs for veterinarians and vivarium managers includes determination of the actual operating needs of a door in terms of locking, latching, closing, power operation, interlocking and security. The most effective contribution to be made to the design process is to develop a clear understanding and description of these functional needs, similar to a space program, that the design team can use. For example, a holding room within a suite could be described as follows:

- Suite entry door provides card-access control and locking for entire suite
- Holding room door is not typically locked or latched; this provides hands-free push/pull access for individuals carrying objects or pushing carts

Fig. 29-1 (a) Holding room door; (b) hinged cover for borrowed light.

- Holding room includes a deadlock and ADA handles to lock the room in the event of an outbreak or isolation need; locking action would be undertaken only by the last person to leave the room.

This arrangement provides easy normal access to holding rooms, while limiting access to each holding suite, but does require a favorable interpretation of building code requirements. Figure 29-1(a) illustrates a typical holding room while Figure 29-1(b) shows the borrowed light cover; specific features include the following:

- hollow metal door and frame, epoxy painted;
- deadlock with recessed pull;
- borrowed light with red glass and hinged cover;
- bumper rail;
- continuous hinge;
- door-edge guard;
- closer with cushioned stop.

A similar arrangement for a typical procedure room is shown in Figure 29-2; this includes these features:

- hollow metal door and frame, epoxy painted;
- deadlock with recessed pull;

Fig. 29-2 Procedure room door.

- borrowed light with clear glazing;
- armor plate;
- continuous hinge;
- door-edge guard;
- closer;
- card reader.

IV. PROTECTION

One of the most challenging issues in vivaria is the protection of door and hardware components from the normal physical abuse of material movement, using kick plates and guards; this is particularly problematic with respect to ongoing compliance with accreditation and maintenance of intact, smooth, cleanable surfaces. Door and frame paint chips are frequent citations during inspections, and the bane of most vivarium managers. ADA-required lever handles work well, but are easy targets for heavy carts on doors with closers when using the contact method to move a cart through a door opening. The final challenge is that protection components and devices are costly and a frequent target of cost-saving or so-called "value engineering" during late design stages. As for other aspects of doors and hardware, the lifecycle cost benefits of adequate protection are easily established and understood.

Selection of appropriate door and frame materials is the first step in protection; as described earlier, both stainless steel and FRP provide a high degree of integral protection. For the majority of projects where those materials are not easily affordable, painted hollow-metal doors and frames will require added protection. However, even stainless steel and FRP materials will be more durable if some added protection devices are provided.

Typical materials used for protective devices are stainless steel and plastic; these may be in sheet or formed configurations. Specific protection components include the following:

- *Plates*: flat sheets applied to doors in areas pushed, kicked, or rubbed by carts; *kick plates* are generally 10" high and full width, located at the bottom of the door; *armor plates* are generally 36"−38" high and cover the bottom half of the door; *push plates* are typically 4" × 10" and are located above the lockset.
- *Edge guards*: formed sheets wrapping the door edge; these are always used at the lockset edge of the door and are full height, sometimes hinge-side guards are used as well, although this location is less subject to impact.
- *Frame guards*: formed sheets that wrap the doorframe, usually at least as high as the strike location, and are effectively a frame on top of a frame. *Roller-type guards* are also available, including cylindrical rollers mounted on brackets that guide carts away from the frame surface. These are very effective but more costly than flat guards.
- *Guard rails*: aluminum or stainless-steel rails similar to corridor guard rails, these are usually located at the same

low (and medium) heights as in corridors. They are very effective in absorbing cart impact, and also provide some door-handle protection due to their distance from the door surface (2 1/2"−3").
- *Lock guards*: aluminum or stainless-steel rails located at the door handles; these guide carts away from the handle.
- *Card-reader guards*: card readers are especially vulnerable, but can be protected with rails if they cannot be recessed into a wall.

V. SPECIAL FEATURES

There are other components and features for special purposes; a common one is a viewing window or port. Most holding rooms require some ability to observe from outside the room; this is typically done with *borrowed lights* (windows within doors), or peepholes. Windows generally need to be covered with lightproof hatches, or include red glass, to maintain control over the experimental photoperiod cycles independent of corridor light conditions. For more information on red glass, see Chapter 33 in this book.

Decontamination using gaseous agents, such as vapor-form hydrogen peroxide (VHP) or vapor-form chlorine dioxide, can be facilitated with ports in the door that allow insertion of a tubing and fitting to introduce the agent into the room. These ports can be permanently installed in each door with the appropriate fittings, or a portable port can be used. In this case, doors are fitted with a removable blank frame screwed or bolted to the door, and a single active port is installed when a room is decontaminated. These ports are typically made from aluminum or stainless steel for corrosion resistance.

VI. SECURITY

Some aspects of planning principles and hardware for door security have been described in earlier sections, but in most vivaria security involves broad use of card access. Within the field of doors and hardware, the following are some of the aspects and terminology. There are two discreet categories of access control devices; hardware items mounted on the door or frame, and electronic devices used to activate the door-mounted items. These two categories are also complicated by the fact that they are typically provided by separate subcontractors (door/frame/hardware and security), and further complicated by their separate engagement by the building contractor and the owner. Coordination of these separate efforts, and the timely engagement of each, is a critical part of a successful project.

- *Access control hardware*: components provided with the doors typically include mechanical items such as electric strikes, magnetic locks, electric locksets and automatic operators. Their proper specification depends on a clear description of their functional purpose in terms of locking, access, and failure mode conditions. Electrical characteristics (typically voltage) also need to be coordinated with the security system.
- *Keys*: although keys are traditional access-control devices, they are more difficult to control, easy to lend or borrow, and usually readily duplicated. Keys also provide no access monitoring of entry and exit events.
- *Access control systems*: electronic access control, such as by means of card readers, is greatly preferred over keys because card distribution is easier to control, users are readily authorized or removed from a control system, and cards can be combined with identification badges. Dual access control is even more secure, using a combination of card access and keypad, or biometric devices that are almost impossible to duplicate. All of these devices are effectively complex switches that send a signal to a hardware device to lock or unlock.

VII. ACOUSTIC AND AIR-FLOW CONTROL

Sound control in vivaria is frequently an issue, whether to isolate noise-sensitive rodents, for behavioral testing, or to contain barking canines. Wall construction provides the majority of acoustic control, but doors are holes in the envelope that can permit sound transmission. Air-flow control is also an issue for isolated spaces such as quarantine, and certainly for biocontainment spaces. Both issues can be addressed with similar solutions.

- *Door construction*: doors are available with acoustic insulation and noise-reduction properties that reduce transmission; properties are measured in Sound Transmission Coefficient (STC) ratings which represent the average frequency in dBa of reduction. A typical sound-rated door, whether hollow metal or FRP, can provide a rating in the range of STC-45 to STC-55.
- *Perimeter seals*: flexible seals at the door perimeter, similar to weather stripping, will seal the crack that allows noise and air to penetrate. These seals are most effective at the sides and top. Bottom seals are more challenging relative to maintenance and operation; *automatic door bottoms* are spring-lifted when the door is open, and drop mechanically to seal to the floor. These are sometimes difficult to adjust on uneven floors, and the moving parts collect dust or liquids that inhibit their motion. Surface-mounted door bottoms are greatly preferred to the concealed type, and can be adjusted and maintained without removing the entire door. Fixed *bottom sweeps* are free of moving parts, but generally do not provide as good a seal.
- *Box strikes*: the door strike in the frame needs to be furnished with a closed box; in drywall partitions an open

strike can allow air infiltration, and if the partition is open to interstitial or ceiling space above it can compromise a barrier or containment envelope.

VIII. BALANCING COST AND DURABILITY: MAKING THE RIGHT CHOICES

Each of the various door, frame and hardware materials and components has different degrees of cost and function; as described earlier, the general principle is that one gets what one pays for in long-term and lifecycle value. Figure 29-3 illustrates a simple matrix of characteristics for major components as guide for selection and specification.

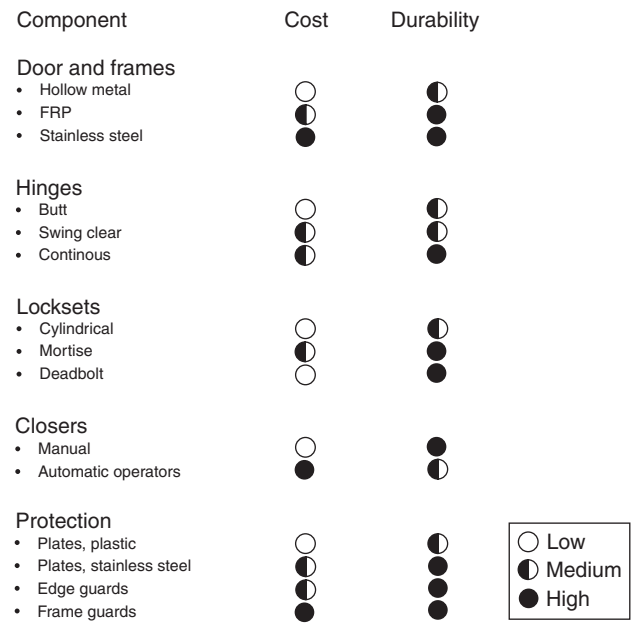

Fig. 29-3 Cost vs durability.

IX. SOURCES OF ADDITIONAL INFORMATION

There are many sources for information on doors and hardware that supplement the basic information presented. Vivarium architects, experienced general contractors, and door and hardware subcontractors can be excellent sources of complete and practical information. For veterinarians and vivarium managers seeking direct information, the Internet can provide unlimited and often daunting amounts of information, but does provide the basis for obtaining the elementary information needed to begin a planning process. All door and hardware manufacturers maintain websites; with recent consolidation in the industry it is easier to find information under product families, and two of the larger groups are Assa Abloy and Schlage, which include many historically-familiar brands of hardware. The BHMA site includes detailed information on quality standards, a glossary, and terminology definitions. The Door and Hardware Institute (DHI) lists manufacturers by component type as well.

Chapter 30

Finish Decisions

Ned Leverage and Clifford R. Roberts

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The *Guide for the Care and Use of Laboratory Animals* (ILAR, 1996; the *Guide*) does not tell us specifically what materials to use or how to construct the animal space. It has, however, served as a starting point to establish industry recommendations in the spirit of providing good-quality housing considering cleanability, disinfection, and maintenance of long-term environmental quality. In short, good husbandry facilities are expected to facilitate yields of quality data. To paraphrase the *Guide* with respect to facility finishes in general, building materials should facilitate efficient and hygienic operations. Finishes should be durable, moisture-proof and fire-resistant, and seamless applications are most desirable. It continues that they should be highly resistant to the effects of cleaning agents, scrubbing, high-pressure sprays and impact. Finally, the facility in general should be well-planned, well-designed, well-constructed and properly maintained to facilitate efficient, economical and safe operation.

The *Guide* does give limited specific insight for floors. It recommends that floors be moisture-resistant and non-adsorbent. It suggests that they be impact-resistant and relatively smooth, but acknowledges that texture may be required. The *Guide* states that floors should be resistant to biological materials and hot water (thermal effects), and that they should withstand the effects of cleaning agents and disinfectants. They should be capable of supporting the weight of racks, equipment and stored materials. It addresses the fact that flooring should be sloped to the drains and that flooring should be monolithic, while acknowledging that minimal joints may be required. Non-*Guide* terms and requirements, such as cost, speed of construction, fast-track construction, lightweight concrete and structural movement, enter as architectural and construction concerns. More recently, end-users have become concerned about materials that repair easily and safely. Materials that have no volatile organic compounds (VOC) and no hazardous air pollutants (HAP) make that possible. Architects and owners are increasingly interested in clean technology as well as consideration about LEED compliance. (The *Guide* delineates specific recommendations for floors, walls, and ceilings separately.)

The specifics of how to go about making the surface finish decisions that will ensure we meet the spirit of the *Guide* are

unanswered. However, the *Guide* is not the only influence at work. In the real world, there are construction considerations that come into play. Cost of construction is a real concern. We will address some of these issues in this chapter.

I. FLOORING

A. Cost

Flooring represents a significant cost in the terms of total dollars, but a relatively small portion of the overall cost of construction when compared to the total facility cost. Epoxy flooring costs on average about $9.00 per square foot, including associated cove base. If the facility costs $400.00 per square foot, the flooring represents 2.25 percent of the total cost. Additionally, the difference between a "better quality" flooring system and the commodity grade represents an even smaller percentage. Cost should therefore never interfere with selecting finishes that are of the highest quality or assure safety and durability, but neither should money be wasted on useless virtues. Further, we are all aware that ultimate cost is not always defined as the cost of the installed product. Costs can also be related to the time lost during installation. If a floor installation price is so low that it seems too good to be a true, it probably is. The elements of cost need to be understood and explored if proper value engineering is to be used. Low installation costs that are out of line likely have not addressed the elements of moisture vapor transmission, chemical resistance, system thickness, proper concrete preparation or concrete crack treatments. Low installation prices often result in functional problems that, although covered in a different budget, can cost more to fix than the initial floor did to install, not to mention the costs associated with the loss of operations inherent in operational downtime.

B. Durability

An important place to start in designing a flooring system is with the issue of durability. Durability encompasses many of the factors mentioned above and, in general, equates to the useable lifecycle of the floor. In general, durability is most affected by moisture. There are two issues with moisture; one is vapor transmission through the concrete, and the other is the degradation of flooring caused by exposure to topical moisture during use.

1. *Vapor Transmission*

Moisture-related problems in flooring are more prevalent today than in the past. Several factors are responsible for that; the main ones being:

1. Fast-track construction resulting in reduced slab drying time prior to flooring installation
2. The use of non-vented pans in concrete construction
3. Inadequate construction specifications for on grade slabs
4. Increased use of lightweight concrete in above-grade slabs
5. Flooring used in animal facilities today has a higher density than the mortar flooring systems used 10–15 years ago.

All of these factors contribute to the increased permeability, moisture content and/or moisture flow through concrete. When determining a quantifiable rate of moisture flow through concrete, the calcium chloride test procedure appears to be the most reliable test available. Manufacturers of most floor coverings believe that vapor emission rates from concrete slabs of greater than 3 pounds per 1,000 square feet per 24-hour period as measured by the calcium chloride method are sufficient to cause flooring problems. They therefore recommend that flooring materials not be installed unless some remedial action to reduce the rate of vapor emission below that level has been accomplished.

Many technical questions about flooring issues are related to moisture or moisture vapor control. It is obvious that the whole moisture issue as it relates to flooring is commonly misunderstood. Initially, the moisture issue was believed to be a liquid water problem exemplified by the common finding of water under pressure in flooring blisters. This phenomenon was referred to as "hydrostatic pressure" (the presence of a liquid under pressure). It was thought that "water" could only be forced through concrete as a result of some unseen force akin to putting a fire hose under a slab. As moisture-related problems became more prevalent, the real problem remained unknown and consequently more misinformation promulgated through ignorance and/or denial. The result has been confusion and, for an industry that responded to the problem too late, a slight lack of credibility for those in the industry looking for solutions.

Moisture problems are not necessarily caused by hydrostatic pressure; in fact, it seldom occurs that way. Some still believe that an on- or below-grade slab exhibiting a moisture problem must have water in direct contact with the slab underside. They expect to find "pooling" or running water far in excess of maximum soil retention levels. While such situations are possible and may occasionally exist, core sampling through the slabs in most cases does not reveal wet or saturated soil. While it is true that the underside of the slab must have exposure to a moisture source in order to transmit it, it is not necessary that it be in liquid form. Moisture problems can occur even in slabs that are not in direct contact with soil but rather reside several feet above a very damp and enclosed environment contiguous with the slab. These conditions provide enough humidity to supply the slab with an adequate moisture source for vapor migration. In reality, moisture vapor transmission through the slab is the issue, not hydrostatic pressure. Moisture vapor is drawn to both higher temperatures and lower humidity, enhanced by the basic principles of osmosis caused by the high alkalinity in concrete.

Moisture vapor remediation techniques are now available to eliminate transmission problems in flooring, and have been used successfully for the past 5–10 years. The initial cost of flooring is increased by the use of remediation, but it is less expensive to treat the problem in the beginning than to be faced later with the potential of floor removal and resurfacing with a new floor. Be sure that the concrete tests being used measure vapor transmission through the concrete, and not the moisture content of the concrete. Regardless of "expert" advice from your general contractor, insist that ASTM F 1869–98 be used as the test. Most flooring formulators accept this test and do not recommend their product be installed if the test results indicate vapor transmission rates of 3 pounds of water per 1,000 square feet per 24 hours or greater.

Damage to flooring caused by moisture vapor differs for mortar and broadcast systems. Mortar systems tend to absorb vapor from the substrate and allow it to dissipate gradually through the system. As moisture absorbs through the floor system, the high alkalinity of the absorbed vapor begins to have a detrimental effect on the epoxy matrix. Eventually, the floor will begin to lose compressive and tensile strength and will begin to crumble under routine weight loads; blisters seldom occur. There is some evidence that urethane concrete-based mortars are less susceptible to deposited alkalis. Broadcast floors tend to block vapor transmission and collect moisture at the bond line of the concrete, resulting in blister formation and, eventually, larger delaminated areas. If moisture vapor transmission is present either from within or under the substrate, no other aspects of flooring matter. The life of the flooring system will be significantly shortened.

We know from research on concrete that the rate of vapor transmission for a given set of moisture, temperature, humidity and osmotic conditions depends on the porosity of the concrete substrate. We know from other research that higher-density concrete results in slower vapor transmission rates. Broadcast flooring was once thought to be impervious and, as such, unable to allow for any vapor transmission. However, based on the knowledge of the ability of broadcast flooring to maintain bond strength to the substrate at vapor transmission rates less than 3 pounds per 1,000 sq. ft per 24 hours, at least some limited porosity can be tolerated by broadcast systems. That understanding became the starting point for the newer technology research into the remediation of the vapor problem.

Another misunderstanding is that moisture problems will not occur if there is a "vapor barrier" (poly sheet or other material designed to stop moisture from penetrating the slab) in place beneath the slab. It is not unusual to find a "vapor barrier" when a core sample is taken through a troubled slab. In fact, most slabs that have problems also have a "vapor barrier" that was installed at the time of construction. Conversely, we have experience with aged slabs that did not have "vapor barriers" installed originally and which even now show low permeability and no evidence of moisture problems. According to some researchers, true and effective vapor barriers do help. H. W. Brewer studied vapor emission from concrete as early as 1965. He demonstrated a dramatic reduction in both the rate of vapor emission and moisture saturation in concrete samples poured directly on vapor barriers when compared to those with no vapor barrier (Brewer, 1965). While true barrier materials are available, they are very costly and difficult to put in place. Due to practical field conditions, conventional "vapor barriers" essentially become ineffective as true barriers the day they are installed. There are obvious requirements in almost every slab for column footers, as well as electrical, plumbing and other penetrations through the underside of the slab. These penetrations are holes in the barrier, and as such violate the "barrier" concept. Further, unless all seams are overlapped and sealed, the seams themselves represent another potential for violation. Ultimately, puncture damage due to normal abuse and wear at the time the concrete is placed may be the largest single factor leading to ineffective vapor barriers. Some within the industry have suggested that vapor barriers may be better referred to as vapor retarders. When selecting vapor retarders, attention must be paid to several factors:

1. Toughness, to reduce punctures
2. Type of material, to reduce the rate of deterioration
3. The permeability of the retarder itself
4. Sealing techniques at the seams and penetrations.

It appears from most studies that while barriers that reduce direct contact of water with the underside of the slab help to reduce subsequent moisture problems, they do not eliminate them. A common occurrence demonstrates this point. If there is a heavy doormat on a concrete step at the back door, when it is moved aside the area that was immediately under the mat is usually darker than the surrounding concrete. The concrete is darker in color because it is damp. Moisture vapor moves upward through an area of concrete at a relatively even rate. The moisture vapor that moves through the uncovered concrete (the area not under the mat) can freely evaporate as it reaches the surface and, because of this, the surface appears dry. Moisture vapor continues to migrate upward through the covered concrete at the same rate as for the uncovered concrete, but the mat traps the moisture vapor at the concrete surface, where it collects between the mat and the concrete and is unable to evaporate. If the mat were flooring material and the back step a facility, there would be a moisture problem. This phenomenon of moisture migration was observed in the study referenced earlier. Brewer demonstrated no reduction of moisture inflow to the bottom side of slabs, regardless of whether the slabs were coated on top or not. He further demonstrated that coated samples had an increase in moisture saturation, proving that moisture continues to inflow in slabs even though subsequent outflow is blocked.

The components of concrete are sand, stone, cement and water. Water is both an essential component of concrete and

the source of some moisture issues. Water is required to hydrate the cement and, ultimately, for strength throughout the life of the concrete. The amount of water required for the hydration of 1 pound of dry cement powder is 0.30 pounds, which represents a water/cement ratio of 0.30. That is a small amount of water and, when mixed with the sand and stone as well as the required 1 pound of cement to produce concrete, would yield a mix too dry to place. For this reason more water than is simply required to hydrate cement is added to the concrete mix to make the mix "workable." This excess water is referred to as the *water of convenience*. After the initial concrete pour, the excess water evaporates from the mix. As a basic principle, water occupies space. When it leaves its space it leaves voids, referred to as porosity. Further, as the water evaporates, it creates capillaries through which the vapor travels. The porosity in concrete is commonly referred to as permeability. Studies have shown that as water cement ratios increase gradually, the resulting concrete permeability increases dramatically. It is critical to maintain low water/cement ratios in order to reduce concrete permeability. Moisture vapor migration through the slab is a direct function of permeability of the concrete, and the primary route for migration is the capillaries just described.

The key factor influencing moisture migration through the capillaries is the differential in vapor pressure between the underside of the slab and the area above the slab. In an environment with a temperature of 55°F and a relative humidity of 100%, the vapor pressure is about 0.214. In an environment with a temperature of 70°F and 50% relative humidity, the vapor pressure is 0.181 (see Table 30-1). The area described above with a vapor pressure of 0.214 represents the average condition found below an on-grade slab. The area represented in the 0.181 vapor pressure represents the condition found within a typical building envelope. By the natural laws of physics, moisture will drive from the area of higher pressure to the area of lower pressure in an attempt to equalize the two. The effects of moisture content below the slab, permeability of the concrete and the alkalinity of concrete combine to increase the water content of the slab. This available water has been described as the "fuel" for vapor pressure, and vapor pressure has been described as the "engine" for vapor transmission. Assuming moisture and vapor pressure differentials are constant at any given time, the rate at which the moisture is transferred to the low-pressure side is a function of the number of capillaries available for transport. Capillaries have been referred to as the fuel lines for vapor transmission. Obviously, if the overall number and size of the fuel lines can be reduced, we can reduce the effectiveness of the engine.

A primary concern of the flooring contractor and end-user is how to determine the potential for problems in advance of installation. It is a given that a source of moisture is likely to be available. Further, if moisture is available it will likely be transmitted through concrete as vapor. There are a number of tests recommended for use with concrete, as demonstrated by Rode and Wendler in 1996. Test methods and procedures must be considered in light of their application to the real issue being measured. Although water and moisture are principal topics, neither is the direct cause leading to flooring damage. It should now be obvious that the real problem is the transfer of moisture vapor, driven by differential vapor pressure from a moisture source through a permeable slab to the area of lower pressure, where it is trapped beneath a low permeability flooring material. Therefore, any test that does not measure the transmission rate of moisture vapor through the slab is inconsequential. Actually, the moisture content of concrete is immaterial if it is static or in equilibrium with its surroundings. It is not until a differential vapor drive is established that the moisture becomes dynamic. It is the dynamic state that needs to be measured, and none of the tests designed to measure the moisture content of concrete measures dynamics. The mat test is indicative of the dynamic state of moisture, but it is a qualitative measurement and is therefore subjective. Only the calcium chloride test

TABLE 30-1

Vapor pressure for Various Temperatures and Relative Humidity Dry Bulb Temperature (°F)/Relative Humidity (in Percent)

	Humidity (%)									
Temperature (°F)	100	90	80	70	60	50	40	30	20	10
80	0.506	0.455	0.405	0.357	0.303	0.253	0.202	0.152	0.101	0.051
75	0.429	0.386	0.343	0.300	0.258	0.214	0.172	0.129	0.086	0.043
70	0.362	0.326	0.290	0.253	0.217	0.181	0.145	0.108	0.072	0.036
65	0.305	0.274	0.244	0.213	0.183	0.152	0.122	0.091	0.061	0.030
60	0.256	0.230	0.205	0.179	0.153	0.128	0.102	0.077	0.051	0.026
55	0.214	0.192	0.171	0.149	0.128	0.107	0.085	0.064	0.042	0.021
50	0.178	0.160	0.142	0.124	0.107	0.089	0.071	0.053	0.036	0.018
45	0.147	0.132	0.118	0.111	0.088	0.073	0.059	0.044	0.029	0.015
40	0.122	0.110	0.098	0.085	0.073	0.061	0.049	0.037	0.024	0.012
35	0.100	0.090	0.080	0.070	0.060	0.050	0.040	0.030	0.020	0.010

(ASTM F 1869–98) measures the dynamics of vapor emission in quantitative terms. Each manufacturer is responsible for developing the standards governing the suitable conditions for the successful installation of their flooring materials. To a great degree, the standards are based not only on the permeability of concrete but also on the permeability of the flooring material and, if applicable, on the sensitivity of recommended adhesives to moisture. Most will state their limits based on the readings as given from the ASTM F 1869–98 test (calcium chloride vapor emission test), and most stated limits are between 3 and 5 pounds per 1,000 square feet per 24-hour period as the maximum allowable vapor emission rate for successful installations. This simply means that vapor emission rates must be at or below those readings, or remedial steps should be taken to reduce the emissions prior to installation. Copies of the ASTM vapor emission procedure are readily available. Since it is almost impossible to stop vapor transmission totally, there are three basic categories for remedial actions:

1. *Penetrants*. These are liquids that penetrate into the concrete and, after reacting with the moisture and alkaline components, form polymerized crystals. The crystalline formation is intended to fill the porosity in the upper levels of the concrete and block the transmission of moisture vapor. These are often referred to as glass membranes, and are in the modified silicate chemical family. The theory is that if the concrete is porous and porosity is responsible for vapor transmission, then simply filling the porosity will eliminate vapor transmission. The theory is good; however, experience with several of these materials has been less than satisfactory. Porosity depends on many variables, and will differ between concrete pours within a given slab. The inability accurately to define porosity within areas of a slab severely limits the ability accurately to fill the corresponding porosity. The result of using penetrants is reduced vapor transmission but continued failures.
2. *Coatings*. Coatings applied topically to the concrete are effective only if they present a lowered permeability that is at once high enough to co-exist with the elevated permeability of the concrete and low enough to bridge the permeability required by the finish flooring. These coatings are thin, generally a few mil thick (1 mil = 0.001 inch), and if applied too heavily have low permeability themselves. It becomes obvious that the coatings are best suited to concrete with lower emission rates, and may best serve as the finish coats. In the final analysis the coating class is not very effective, as low-pressure side barriers must be semi-permeable membranes, and as such do not work well in high-tech applications as finish coatings.
3. *Membranes*. This can be a misunderstood term. Generally, membranes are thought of in terms of their positive side potential. The most obvious example of positive side membranes is the application of waterproofing to the outside of a block wall of a below-grade basement. In this case, the membrane is placed between the substrate (the block) and the source of the water (the soil). The membrane serves as a barrier to water penetration through the block and ultimately into the basement. However, the membranes described here are negative or low-pressure side membranes. They are generally cement-based or polymer concrete-based, and are applied to the top side of the slab to reduce vapor transmission after moisture has entered the slab. In this regard, they are on the low-pressure side of the concrete. Due to their chemistry, these materials are compatible with moisture and are not affected at the bond line by differential permeability. They close or reduce capillary size at the concrete interface, thereby reducing vapor transfer rates. In addition to reducing the permeability gradient, they appear to absorb moisture within the membrane layer. This treatment is currently the most effective; installers can issue significant installation warranties if pre-testing of vapor transmission gives satisfactory results.

2. *Topical Moisture*

Topical moisture, probably the primary thought when the *Guide* referenced moisture-resistant and non-absorbent, is not generally addressed as a floor durability issue. To fully appreciate the effects of topical moisture, we first have to understand the history of applied floor finishes. The evolution of major flooring systems began with latex mortar systems. These early systems worked well over time because, at that time, the abuse level to floors from daily use was limited primarily to impact. Although surface chipping did occur, it was accepted as an inevitable consequence of operations. Chemical abuse was limited to alkaline detergents that mimicked common household detergents, mostly used to clean small, galvanized caging and rack units. The detergents were innocuous and had little impact on flooring. Additionally, latex systems are generally compatible with topical water.

As animal holding protocols changed to include stainless-steel cages, the cleaning regimes began to include acid cleaners. Since the latex flooring lacked chemical resistance to acids, latex floors began to fail. Epoxy mortars were the natural replacement. Epoxy mortars utilize installation techniques that had been acquired from latex mortars so there were skilled mechanics readily available for the new flooring materials. It was further understood at the time that epoxies had better chemical resistance; the shift to epoxy was understandable. As time progressed, the industry began to understand that although epoxies used in that generation of technology were more chemically resistant in general than latex, they were still not up to the task of withstanding an ever-expanding and more aggressive line of acid cleaners and disinfectants.

The industry also began to understand that mortar flooring systems were inherently porous and absorbed liquids and microbial nutrients into the body of the floor through chipped areas in the floor surface. The absorption of liquids

and nutrients created an aggressive environment for anaerobic microbes to flourish. Anaerobic metabolism includes the breakdown of epoxy substrates and the production of chemical byproducts that also destroy epoxy molecules. Since moisture enters through chips in the floor and carries materials that begin the destruction of the floor, it would appear that the use of mortar flooring systems would not be in the spirit of the *Guide*. The requirement for non-absorptive flooring is violated by porous systems.

In the 1980s, the industry realized that porous floors could not only be absorbent but, because incorporated air expands and contracts as it changes temperatures, could also be a contributor to the laboratory environment. Based on this new understanding, the animal science industry began to prefer the use of resin-rich systems, commonly known as broadcast systems. The broadcast systems are virtually non-porous, and therefore the damage from impact is isolated to a localized area. Since the damaged area in broadcast floors is much smaller, the floor is easier to repair. The lack of porosity meets the spirit of the *Guide*, since broadcast systems are non-absorbent and consequently do not degrade as do mortars. Broadcast flooring satisfied the moisture-resistance and non-absorptive issues, but another moisture problem was created – one in which low-permeability flooring, including some resinous floor systems, became chipped or eroded while wet operations continued.

An aspect of substrate moisture that is rarely dealt with is water introduced through the top of the slab. This water is generally a result of normal work procedures requiring wash-down or cleaning, especially on a repetitive basis. Bruce Suprenant examined some effects of topical water on subsequent vapor emission rates on uncovered slabs (Suprenant and Malisch, 1998). His data demonstrate, among other things, that cured concrete slabs will absorb water topically, which subsequently results in increased vapor emission rates. His data are based on a measured exposure for short periods of time (hours) with some dramatic results. Information regarding the effects of prolonged exposure (i.e., years) to wash-down procedures was not found. However, it is possible, based on Suprenant's information, to predict that absorption from topical moisture does occur, and that extended drying periods following topical exposure are required to reach acceptable vapor emission rates. Water absorption from topical exposure can also occur in areas that have existing flooring systems. The most common of these is tile. All tile products have seams or joints. Glazed and quarry tile floors have pronounced joints through which water freely penetrates to the substrate unless special joint compounds are used. Although we do not normally associate vinyl composition tile (VCT) installations with wet environments, there are facilities in which wet functions take place over VCT flooring. As seams begin to separate and lift in these systems, water gains free access to the substrate as well. In some instances, ceramic tile floors are installed over mortar setting beds. The setting bed potentially becomes a sponge, readily absorbing and releasing free water. Just as with concrete, porous flooring absorbs moisture, some of which will be transferred to the covered slab. The reason for addressing this aspect in the moisture section is that, in renovation, there is often a requirement to remove and/or resurface these porous flooring systems. Renovation projects are often associated with area shutdowns and fast-track timing. Care must be taken to assure that moisture readings are taken and vapor emission requirements are acceptable prior to installation of new flooring systems. Additionally, specifications requiring new flooring to be installed over existing systems are often written to save time and money. Trapped moisture within a system can produce vapor emission from concrete. Therefore, in these instances care must be taken to assure that moisture is not present within or under the existing system.

3. *Chemical Resistance*

With moisture issues settled, chemical resistance should be considered the next most critical issue in flooring durability. Understanding the level of chemical resistance needed in an animal facility has been an evolutionary process. As an industry, the trend has been from alkaline detergents to acid cleaners, and from mostly innocuous quaternary ammonia disinfectants to chlorine dioxides and a host of other chemicals. Additionally, chemicals are now used more throughout the facility, when use was formerly limited to the cage-wash or surgery. It has been difficult to predict animal research chemical requirements.

Resin quality is the factor most responsible for long-term non-mechanical properties of the flooring system. Chemical resistance is the feature of resin quality that will govern performance in these potentially abusive environments. Flooring resins are composed of two primary components; base resin and a hardener. The chemical resistance properties of a particular flooring system are primarily the result of hardener properties. Formulators do not generate their own hardener product; they simply modify the chemistry of the hardener and corresponding resin component to allow for the proper balance in reactive sites required for proper cross-linking to form the final product. Since the final cross-linking is a product of the hardener, and since formulators use different hardener systems available from hardener manufacturers, the effects of chemicals are not predictable between like-named resins from different formulators. Simply put, not all chemically-resistant products perform alike. The flooring industry as a rule, however, publishes chemical resistance charts with broad implications – for example, epoxy resins tested for a long list of "reagents" including lipstick and beer. The industry uses these charts to report the resistance of a generic class of resinous coatings to a broad range of test chemicals. It should be noted that charts are useful only as a general guide.

Chemical resistance is very specific to each resin product, and should not be judged in categorical terms. Testing supports

this position. For example, there is often a remarkable difference between the reactions of a specific resin to reagent-grade chemicals as compared to its reactions to commercial cleaners containing the same chemical. This difference is present even when the two are tested under the same conditions and at comparable concentrations of the chemical in question. There is also a difference in the level of aggression between commercial cleaners containing comparable concentrations of the same test chemical. For example, commercially available 37% phosphoric acid cleaner will be more aggressive to specific flooring than a 37% phosphoric acid reagent solution is to the same flooring sample. In such instances, the difference in reactivity of a flooring resin is attributed less to the test chemical than to the surfactants and other additives incorporated in the commercial cleaners. These ancillary chemicals are designed to enhance the effectiveness of the active reagent by increasing surface wetting, among other things. These ancillary chemicals are absent when testing reagent-grade chemicals, but are present when using commercial formulations in your facility. When an end-user has questions about the performance of a flooring material to phosphoric acid, for example, they generally consult a formulator's chemical resistance chart. Although the chart indicates resistance, field application of the commercial compound may be quite different. Consequently, it is important to not interpret chemical resistance charts listing pure test reagent as applying perfectly to a specific facility application. Flooring products are best tested against commercial formulations that are part of the end-users protocol in order more accurately to predict the long-term performance of the flooring system. Formulator published chemical resistance lists should be used only as an initial guideline or aid to selecting the proper chemical family to use as a seal or top coat.

Resin formulation is a precarious balance between esthetic qualities, physical properties and performance characteristics. As one trait is altered, the remaining ones are generally affected. Epoxies are too often thought of as a commodity item, implying little or no difference between two products and that if any difference does exist, it is inconsequential. In some industrial flooring applications, such as warehousing and process manufacturing, the theory of inconsequential differences may be true. The warehouse solution, however, is unlikely to perform well in biomedical, pharmaceutical or other more critical applications. The challenge is to determine what the user really needs from a flooring system. A successful approach has been to be proactive in identifying the chemicals used in an industry, to understand their application and handling, to test the commercial formulations of these chemicals on all new and existing resins proposed, and to do the testing for meaningful intervals of time. In this manner, we can customize a flooring system using specific resins that will withstand the intended abuse with predictable performance results. All commercial chemicals to be used should be tested in both concentrated form and at recommended use-rate dilutions. The rationale for use-rate dilutions is obvious, as it is the expected long-term exposure. Concentrate testing should be included because spills and leaks occur where the chemicals are stored and dispensed.

a. Test Procedure

Resinous materials are applied at the final film thickness recommended for actual field application and allowed to cure for 7 days to reach full chemically-resistant cure. Test chemicals are applied using soaked cotton balls placed on the surface of the cured resin. The cotton balls are kept wet with the test chemical for the duration of the test period. The cotton balls are then removed and the wetted surface is wiped clean for observation at 24, 48 and 72 hours, and at 7 days. While making each observation, the cotton ball is individually removed, the spot observed and observations recorded, and the cotton re-soaked and immediately replaced. Each exposed area is therefore without test material for a minimal period. Tests are conducted for the full 7 days unless there is total film failure prior to that time. If total failure in a given spot is observed, that spot-test is stopped. Observations are made in the following categories and recorded for comparison purposes:

1. Staining
2. Pigment leaching
3. Discoloration
4. Film swelling
5. Film softening
6. Loss of gloss
7. Surface etching
8. Film destroyed
9. Other surface effects.

The most obvious effect is referred to as staining. Staining occurs most frequently with no effect to the overall performance of the flooring system. It is a blemish that affects the esthetic acceptability of a floor only. Nonetheless, it is an undesirable consequence. Most of what we see as staining is really discoloration, not staining. True staining is a discoloration imparted by a dye. The dye penetrates the flooring material and cannot be removed by chemical intervention or by scrubbing. Another condition commonly referred to as staining is discoloration, which is really pigment leaching, where the chemical attacks the flooring pigment and changes the color; no dye is required. Often in such cases the performance properties of the flooring are not affected. A third condition of discoloration is an effect often seen as yellow to brownish spots. This is a typical discoloration caused by nitric acid due to direct chemical attack on the resin. If prolonged exposure were to occur, the coating would deteriorate and completely fail. Since esthetics are important to end-user satisfaction, it is recommended that as many sources of discoloration to the resin be eliminated as possible. Therefore, clear resins, not pigmented resins, are generally recommended to eliminate

the effects of pigment leaching. True staining cannot be completely eliminated, although certain resins are more resistant to staining than others. Comparisons of the pigmented resins with the clear resins tested, however, do allow the conclusion that clear resins maintain esthetic value better than pigmented resins.

Film swelling occurs when the resin absorbs the chemical and actually gains volume. The softening can initially occur as a surface effect, but eventually the flooring can have reduced performance properties and deteriorate to the point of failure. Softened floors will "cut" with heavy-wheeled traffic, and can quickly erode to the substrate.

Loss of film gloss and surface etching may be difficult to demonstrate. In some instances, these areas simply have no gloss (minor etching) and have no apparent change in surface texture or smoothness. As this condition progresses, the surface texture is etched and therefore acquires a fine profile much like acid-etched glass. With time, both can cause failure if the chemical cause is strong enough, but both conditions will cause cosmetic blemishes. The white appearance of total film destruction is a result of total erosion of the seal coat exposing the white quartz granules in the flooring. Two chemicals tested that resulted in total failure were glacial acetic acid and methylene chloride, both reagent grade.

4. *Quality Control*

It is a logical deduction that participation by the end-user in the procurement process will eliminate a host of problems. The question is how to accomplish end-user involvement and still have a competitive bid process. We suggest using a comprehensive quality-control program and specification development procedure as part of the selection process for flooring. The program should also be incorporated into the flooring installation protocol through inclusion in the specifications. The following program has been used successfully on both new construction and renovation projects with success. The essence of the protocol is as follows:

1. Competing contractors submit two $4' \times 8'$ finish floor samples on plywood backer.
2. The floor systems submitted are those recommended by the formulator and installing contractor for the proposed installation.
3. The finish floor samples shall be accompanied by material information, including lot numbers of the materials used for the sample (the same as those proposed for the project).
4. The end-user observes panels for finish characteristics such as gloss, finish texture, and general appearance. The panels or portions thereof, can serve as a standard for the final installation.
5. The end-user performs chemical resistance tests on one panel and tests the second for wear properties using floor buffers, cart or other traffic and/or normal cleaning protocol.
6. The selected system is then installed using the lot numbers initially indicated on the test panel submission.
7. Areas too large for material volumes produced in a single lot number will require testing of each manufactured lot prior to that lot being used on the project.
8. Final approval should be with the end-user.

Although the protocol is time consuming, it accomplishes several critical objectives essential for a successful floor installation. The end-user is involved in the final selection. The final flooring selection is based on quality issues and measurable differences, not subjective comments. The end-user's personnel test the end-use application under near field conditions. There are no surprises later for any party involved. The installing contractor and resin supplier both assume ownership in the project and cannot claim ignorance later. What does this require of the end-user? Check the specific flooring system you propose to use against the specific chemicals in your facility. Do not rely wholly on charts, but use them to lead to a resin family that is most likely to suit facility needs. Require the flooring professional to provide samples in the quantities required for adequate chemical testing in your facility. Do this in advance of awarding any contracts.

5. *Concrete Slab Joints*

There are three types of joints in concrete slabs: pour joints, expansion joints and control joints. Pour joints are joints that occur between concrete pours. They delineate one pour from another, and are merely beginning and ending points. Generally, there is a keyed metal divider that separates the pours. Pour joints are not intended to be moving joints.

Expansion joints are designed to allow movement to occur as either expansion and contraction, or settlement. The use of expansion joints is intended to eliminate uncontrolled cracking in the concrete. Generally, expansion joints are wide joints and the adjacent slabs are separated by soft materials. These joints are designed to move.

Control joints are joints that are literally cut into the wet slab and are placed in areas of the slab where movement is expected so that as the slab needs to move it will crack at the control joint as opposed to exhibiting random cracking.

The need to properly detail each type of joint so that they do not fail is as critical to the durability of a flooring system as are moisture remediation and chemical resistance. Improperly treated joints will either crack (open) from contraction of the slab, or buckle and/or delaminate from the compression of the joint caused by expansion of the concrete. Lateral rotation or uneven settlement of adjacent slabs will also cause cracking and/or delamination of the flooring as well. The *Guide* recommends that flooring in the vivarium be monolithic, while acknowledging that minimal joints would be acceptable. This recommendation ignores the potential for damage to the floor and the problems associated with repair. We recommend the operationally

conservative approach; treat all joints as moving joints and, as such, reference all joints through the floor, caulking them with an elastomeric caulk to ensure they are sealed. The caulk is a maintenance issue, and needs to be evaluated periodically to assure it remains sealed. This is a minor inconvenience when compared to the noise and dust associated with floor repair that could otherwise occur.

6. *Floor Sloping*

Finally, the *Guide* indicates that flooring should be sloped to drains. Flooring resins in general function better over time if they are not in constant immersion conditions. Low spots that allow water to collect create immersion conditions. Water puddles are also a safety hazard to employees. Cleaning chemicals that may be in the pooled water can also concentrate by evaporation and thereby extend chemical exposure to the floor. However, once again, cost can become an issue. Sloping the floors is most expensive, but also best and most functional, when done by the flooring contractor. Sloping is less expensive when done at the time of the concrete pour, but the logistics of the sheer material volume while placing concrete, as well as load shifts during placement, make precision sloping impossible. The recommendation to assure water flow to the drain is to slope at a minimum rate of 1/8″ fall per foot of linear run to the drain. For animal pens where solid material will be present, 1/4″ per foot is recommended.

7. *Point Loading*

The most recent durability concern is the use of heavy rack systems with minimally resilient autoclavable casters. We have reached a crossroads where point loading of heavy racks is reaching the compressive strength limits of flooring systems. Larger cage racks (weighing 1,000–1,500 pounds) afford the end-user reduced space requirements, thus more efficient space utilization and lower space costs will become more prevalent. When the point loading of the rack exceeds the compressive strength of the floor, the flooring begins to show minute fractures in the resin component that leaves white tracks where the caster travels. This problem will only be eliminated when flooring physical properties improve significantly, or point loading of casters is reduced. Until then, it is a looming problem with limited solutions available.

C. Ever-Changing Flooring Needs

No doubt, everyone associated with the flooring process has been frustrated from time to time. Much of the frustration has been caused by the need to change the flooring product to meet the ever-changing needs of the industry, but change never is as rapid as the need for change. Animal research is driving the development of more durable floors.

The flooring industry is offering alternatives to current flooring products. The newest products are a result of improved and innovative chemistry that contain no volatile organic compounds (VOC) and no hazardous air pollutants (HAP). This means there are no volatiles to off-gas into the environment and no hazardous vapors to breathe. Not only is this an advantage for the research environment during occupied renovations; it is also safer for the contractor's crew and anyone else associated with the process during new construction. A notable example is ultraviolet light (UV) cured materials, which enhance tighter cross-linking at cure and yield better chemical resistance, better physical properties, and a more controlled immediate cure.

II. WALLS AND CEILINGS

To paraphrase the *Guide* once more with respect to interior finishes: building materials in general should facilitate efficient and hygienic operations. The finishes should be durable, moisture-proof, fire-resistant and seamless. Additionally, they should be highly resistant to the effects of cleaning agents, scrubbing, high-pressure washing and impact. Overall, the *Guide* states that finishes should be well-planned, well-designed, well-constructed and properly maintained so as to facilitate efficient, economical and safe operation. The finish of walls and ceilings should be smooth, non-absorbent, free of imperfections, cracks and unsealed penetrations, and with no imperfect junctions. Finally, it proposes that the use of devices such as wall bumpers or floor curbs to protect the finish integrity of the wall should be considered. Ceilings are afforded the same basic requirements, but it states that ceilings made of permeable materials are not recommended. As with flooring, the wall and ceiling finishes in the vivarium must be sustainable and durable.

Decisions regarding construction materials and finishes are to a great extent affected by both architectural and programmatic requirements. Architectural concerns such as cost of construction, availability and cost of materials and finishes, speed of construction, labor availability, structural preferences, experience, familiarity with materials and local building codes all play a significant part in the construction recommendations.

The most commonly used construction materials for walls have been CMU (8″ × 8″ × 16″ concrete masonry units) and gypsum board (dry wall). The two have very different construction personalities, and each dictate the use of a process specific to that material to attain the desired finish.

CMU surfaces are not smooth. The raw finish of the block is rough, porous and "open." The surface of CMU must be filled and rendered pinhole-free prior to coating in order to accomplish a satisfactory finished surface. The initial step is to use a product appropriately named block filler. Once the block filler is applied and cured, it is covered with a durable coating. Historically epoxy resins have been used, since they provided

the best performance properties of hiding power and durability. They have proven to be susceptible to chemical attack, they wear through in heavy-use areas, and they chalk or discolor with age and exposure to UV. Formulators now have developed urethane resins that are essentially solvent-free and these resins are replacing epoxy as the product of choice. Urethane coatings provide a final finish that is denser and exhibits better chemical resistance than epoxy products. These basic properties of urethanes yield an increased durability and, although more expensive initially, lower long-term operating costs.

Both urethane and epoxy resins are available in three basic formats; solvent-based, water-based and 100 percent solids (near solvent-free). There are some distinctions between the three.

The first difference is safety. Solvents are health risks as well as potential fire and/or explosive agents even while incorporated in the coating resins. For years the most popular formulation available for epoxy wall coatings was the solvent-based formulation, but recently solvent-based products have been recognized as hazardous. Today, several agencies (federal, state and local) are starting to monitor and regulate coating emissions. Safety-conscious businesses are beginning to monitor solvent emissions within their facilities, apart from government regulations. In recent history, most solvent-based coatings contained 40 percent of a mixture of solvents. To quantify the environmental impact of solvent-based coatings on the air quality in a facility, examine a scenario that assumes it requires 100 gallons of a solvent-based coating to paint a given area of the facility. Since the product chemistry requires that the solvents evaporate before the coating can cure or harden, 40 gallons of solvents would evaporate unabated into the facility before the coating could cure. If that quantity of solvent really was dumped on the facility floor, it would justifiably result in a HAZMAT response. Even with some of today's more "environmentally friendly" resins, which contain only 18 percent solvents, the equivalent scenario still results in dumping 18 gallons of solvent into the facility. The truth is that, with the availability of today's technology, the use of solvent coatings is simply environmentally irresponsible. There is a safer way to accomplish the task.

Aside from the obvious solvent dangers, solvent coatings nevertheless offer some benefits to the contractor, and many of these coatings are still being used today. They allow for a longer pot life (the length of time between mixing hardener and resin together and the point at which the mixture gels), which allows the installer more working time between mixes and better overall production efficiency. The coating process is therefore accomplished faster and with less labor. In a solvent-based coating, the viscosity of the mixed coating can be adjusted easily to allow the coating to flow more evenly onto the surface and result in a more uniform appearance. Solvents are less expensive than pure epoxy resin, so the substitution of a less expensive solvent for costly resin reduces the overall cost of the coating. That translates to the major cost advantage: lower material costs and lower labor costs produce lower coating prices.

The thinner viscosity of the solvent coating, however, is a disadvantage to the end-user. The designer's intent is to have the wall coating applied at a thickness that promotes durability, and 12- to 15-mil DFT (dry film thickness) applications appear to be the optimum point for wear vs cost ratio. Solvent coatings are thin and can only be applied at about a 4–5 wet mil thickness before the coating runs down the wall and looks unsightly. After the solvent contained within the mix evaporates, only 85 percent of the original wet mil thickness remains, leaving a final DFT (dry film thickness) of 3.5–4 mils per coating. Consequently, solvent-based coatings generally are not applied in the optimum range and will not perform to expectation.

Waterborne epoxy and urethane coatings are available in which water essentially replaces the organic solvent as the diluent. The chemistry that allows oil and water to mix as it does in this case is safer than conventional solvent use, and also has the user-friendly attributes of solvent coatings. Similarly, the water must evaporate before the chemical reaction for hardening can complete. The resulting difficulty in building thick film applications, as with solvent-based chemistry, exists with water-based resins as well. These resin formulations also yield a thin application from which a percentage is lost to evaporation, yielding a thin final dry film thickness. Further, the product does not have the high sheen, high chemical resistance or wear properties that the solvent resins possess.

Coatings termed "100 percent solids" are chemical formulations that are free of harmful solvents and water. In spite of the name they are not solid but liquid. These 100 percent solids coatings have a short pot life, and therefore require mixing in small batches in order for the mix to remain as fresh and forgiving as possible. They therefore require more labor to install, and are definitely not user friendly.

The 100 percent solids coatings, however, are state of the art, and should be the preferred coating for several reasons. Since these coatings do not contain harmful solvents, they are safe for use in occupied facilities and will leave fewer airborne contaminants within the facility HVAC systems when the building is ready for occupancy. This condition can be critical to some olfactory research. Without the dilution that solvents afford, the 100 percent solids materials are highly viscous, allowing for a thick wet-mil application. Since there is no shrinkage from solvent or water evaporation, the final dry film thickness is the same as the initial wet film application (7 wet mils applied equals 7 dry mils cured). Consequently, these coatings result in a high film build and excellent durability as compared to the solvent- or water-based materials. Film hardness, gloss retention and chemical resistance are also positive performance characteristics with this class of materials. Because the coatings can be applied at greater thicknesses, the overall durability and lifecycle is improved over the other

classes, which means lower maintenance costs and reduced lost facility operations during repainting.

Providing a pinhole-free surface presents the greatest difficulty with CMU walls. The standard definition of a pinhole is any hole through the surface that is detectable under 7× magnification (Federal Specification TT-C-550C). Simply take a 7× magnifying glass and examine the wall; if there are visible pinholes, then the wall is not acceptable to federal specification. CMU by nature has a rough absorptive surface and allows free exchange of air through the surface if it is not completely sealed. Cracks, imperfect junctions, chips in the surface and pinholes are considered unacceptable in animal holding facilities because they represent places for nutrient and microbial infiltration from the animal environment to be absorbed into the block interior. These contaminants can be recycled back into a clean animal environment as temperatures and other factors cause the block to exhale.

Pinholes are seldom a problem with drywall finishes. The surface of drywall is absorptive, but it is smooth, denser, slower-breathing and easier to seal than CMU. The process for coating drywall involves an initial seal using either a special primer or a self-priming resin to penetrate the surface and seal airflow. This is followed by at least two coats of a resin that is 100 percent solids. For the optimum performance vs cost ratio the final coating, not including the primer (or block filler in the case of CMU) should be 12–15 mils counted as dry film thickness (DFT). Coatings on both drywall and CMU can chip on impact. CMU as a structural unit can withstand heavy impact and still maintain structural integrity while drywall will crush, often leaving a hole that exposes the unclean interior wall space. There are now variations of drywall panels that are much more resistant to impact and moisture damage, but add little additional cost to the wall.

Both drywall and CMU will absorb water caused by broken pipes, leaks within the wall or penetration through unsealed surfaces. Water can cause failures in both if the water absorption is excessive but the damage is noticeably different. Coatings will peel from block walls or drywall, especially if the block filler contains PVA as a thixatrope. In the case of drywall, the coatings may peel, or the entire wall may be destroyed if the water quantity is sufficient.

As for the performance characteristics of the coatings themselves, they are cost-effective in most applications but can fail in heavy abuse scenarios. Impact, high-pressure washes and direct contact with primates, dogs and large animals are some of the conditions considered to be heavy abuse. In these conditions, non-standard coatings or finishes are recommended. These include installing flooring material to the wall surface as high as is necessary to establish the required protection; this solution is both esthetic and effective. Installing fiberglass mat over the wall surface and encapsulating it in resin is another means of increasing and enhancing the performance of wall coatings. These finishes increase the impact and abrasion resistance of drywall and cement board substrates, as well as providing much improved chemical resistance.

Regardless of the chemical formulation, all coatings have recommended recoat windows – a time from the initial application within which a following coat must be applied to assure good intercoat adhesion. Most of the windows are from 24 to 36 hours long. Recoating outside that window often leads to the kinds of failures commonly seen in animal facilities. Paint that peels or flakes easily is evidence of poor intercoat adhesion. Coatings therefore need to be applied in concert from the first to last coat, with particular attention being paid to recoat windows. Work outside normal work hours may be required in order to accomplish the required timing. Renovation work or simple repaints should never be attempted without a complete mechanical abrasion to the existing coating on the walls and ceilings. Mechanical abrasion will allow for a good mechanical bond between old and new coatings.

The use of composite wall panels consisting of a variety of core materials and finished with fiberglass gel coat resin is another way to provide durable wall finishes. In the case of composites, the panel can be designed as a structural unit that resembles drywall in thickness and in many cases in overall dimension (i.e., 4′ × 8′ × 5/8″). The composite panel core can be drywall or other hard board product, foam, or other synthetic material. The surface of these materials can be laminated with FRP (fiberglass reinforced plastic) sheets. The result is a wall product with superior performance when compared to bare drywall and/or coated hardboard products. Composite panels allow all the advantages of hollow wall construction. Because they are an engineered product, composite technology can provide for most of the criteria referenced in today's facility requirements:

- they have the only true smooth surface finish available;
- core materials can be selected that are totally moisture insensitive;
- both core and surface materials can be designed to be extremely impact-resistant;
- the surfaces are manufactured free of cracks and pinholes;
- since they are manufactured and finished in controlled environments, there are few imperfect junctions;
- the gel coat resins can be designed to withstand a broad range of chemicals;
- the surface is durable enough to withstand high-pressure washing;
- no down time is ever required for painting;
- the construction joints between the panels can be sealed using a variety of techniques, ranging from sealed flat batten strips to several seamless joint techniques.

The major disadvantages of composite panel construction are the availability of experienced installers, the cost of the material and the installation labor, product lead times, and limited flexibility of the product. Some core materials of

composite panels may not pass local fire codes and so their use may be discouraged. It is important to check local codes during product selection and to assure that the engineering of the panels being considered is mutually compatible.

Ceilings have many of the same coating issues as walls. Although ceilings are not made of CMU, they are sometimes simply the product of the underside of the concrete slab of the floor above. In this case, the concrete should be treated like CMU and filled with block filler prior to applying the coatings. As with walls, this procedure is the only way to assure that the ceilings are pinhole-free.

As with walls, the most common cause of failure in gypsum ceilings is water – initially seen as peeling paint, then as failed gypsum board. Steam that escapes from cage-wash and autoclave doors against the ceiling can also cause coatings to fail. Placing a stainless-steel hood with an exhaust adequate to capture and remove the expelled steam will reduce the problem greatly. Additionally, the use of suspended or hard ceilings composed of composite panels that are insensitive to those elements will also relieve the problem. Suspended ceilings should be sealed to isolate the room from the interstitial environment. This can be achieved using gaskets and lock clips. All through-ceiling penetrations should be sealed as permanently as possible, using a minimum of caulk to seal the opening or by using fiberglass mat encapsulated within the coating wrapped at the ceiling/penetration junction.

Basically, wall and ceiling finishes should be as smooth as building resources will allow, sealed from the non-controlled environments that are the adjacent area, and free of surface imperfections that will interfere with cleaning and disinfecting. They need to have the chemical resistance required to withstand cleaning and disinfecting chemicals, and should be tested for chemical resistance in much the same manner as floors. They need to be moisture-insensitive and designed with functional performance qualities that match the environment they are intended to create.

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Chapter 31

Special Fixed Equipment for Research Animal Facilities

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I. INTRODUCTION

The major fixed equipment in laboratory animal facilities is involved in the functions of washing and drying cages, disposal of spoiled bedding, dispensing clean bedding, cleaning and filling water bottles, and the sterilization of portable equipment and supplies. Other important fixed equipment includes the security and access-control system and the fire alarm and sprinkler system. Originally, many of the above-noted functions were done by hand and/or made use of equipment manufactured for other industries – for example, bottle washers were adapted from equipment used to wash milk bottles, and cage washers were adapted from equipment from the food services and processing industries. Today, many companies are specializing in servicing the laboratory animal industry and are prepared to work closely with design teams to meet the need for both standard and custom-designed and -sized equipment.

Decisions on the use of special equipment for lab animal facilities depend on many criteria, which may vary in importance or relevance to the team members making the decisions (Hayden, *et al*., 1989; Klein *et al*., 2001). As the sophistication of animal-based research and the care for the animals has increased, so has the sophistication and specialization of the associated equipment. The need to streamline operational

processes to reduce operating costs has also been an important driver (CDCRLF-1, 2000). In addition, having the appropriate equipment reduces project cycle times and maximizes the use of the research animal facility (Hayden *et al*., 1989).

Prior to selecting specific equipment, it is essential to understand the animal requirements of the research program the facility will support and the animal-care program that will be implemented. Other considerations for selection include flexibility of use, cost, return on investment (ROI), special utilities or space that may be required for operation, special training, maintenance needs, and operational advantages. Most important are the benefits to animal care and welfare, plus meeting or exceeding research goals. These factors, along with any advantages to personnel, should be considered when developing the business case or meeting the scientific and animal needs for purchase and installation of the special equipment (CDCRLF-1, 2000; CDCRLF-2, 2000; CDCRLF-3, 2000; HLW International, 2005).

The ability to automate operations through the use of special equipment is likely to be the single most important factor to consider. Automation using special equipment not only reduces labor and operational costs, but may also minimize renovation or construction costs. Work practices, facility design and overall work flow may also be affected in a dramatic fashion (Frankenberg *et al*., 1998; Klein *et al*., 1999; Terpeluk *et al*., 2001).

II. CONVENTIONAL CAGE SANITATION EQUIPMENT

A. General Comments

Adequate control of the research animal's microbial environment is dependent to a large degree on having the proper cage sanitation and sterilization equipment. Sanitation involves destroying undesirable vegetative microbial organisms on the surface of the object being sanitized. This is as compared with sterilization, which involves destroying all microbial organisms in or on the object being sterilized.

Hand washing of cages and reliance on chemical disinfectants to achieve sanitation is an option but is not recommended, even for small facilities. Not only is it labor-intensive; it is also inconsistently effective under normal operational conditions, increases the potential for leaving unacceptable chemical residues on the cages, and exposes personnel to chemical hazards. Sanitation is best achieved by using mechanical washers and water at temperatures in excess of 180°F (82.2°C) (ILAR, 1996). The 180°F standard was apparently first published by the National Sanitation Foundation, which set standards for commercial dishwashers (NSF, 1953). Effective sanitation is time- and temperature-dependent (Small and Dietrich, 2007). Sanitation can be achieved at 180°F with 1-second exposure; however, it can also be achieved at lower temperatures for longer exposure times, e.g., 15 seconds at 161°F (71.6°C) or 30 minutes at 143°F (61.7°C). (Wardrip *et al*., 1994). Sanitation can be achieved at even lower temperatures with the use of higher levels of wash chemicals, but at a higher cost. To assure adequate sanitation, the control systems for contemporary washers may be programmed to delay the initiation and suspend completion of a wash cycle if water temperature is below 180°F. Given that effective sanitation can be achieved with 1-second exposure to water temperatures of 180°F or higher, consideration could be given saving energy by using lower temperature water, e.g., 140°F (60°C), for all cycles except the final rinse cycle, which would be 180°F. The lower wash-water temperature has the advantage of being compatible with more types of washing detergents. Hence, selection of and installation of a machine with programmable temperature and cycle times is well worth the investment in any sized facility.

Planning of cage sanitation equipment requirements should take place in the programming phase of the project so that the proper amount of space can be allocated for the cage sanitation area in the programming phase. The goal is to determine the type, size and number of cage-washers, autoclaves and other equipment that will be required for a given facility based on the calculated cage sanitation workload. This requires knowledge of the species to be housed, maximum cage census for each species, and sanitation practices to be followed (e.g., cage-change frequency). For example, a 10,000-cage mouse facility will need to process (clean and possibly autoclave) 5,000–20,000 mouse cages per week with all their parts depending on the planned cage-change frequency (once every 2 weeks, once a week, or twice a week). In addition, cage racks, transport carts and water bottles, along with miscellaneous other items, will need to be sanitized. Once the workload is established, the type and size of the sanitation equipment required to efficiently sanitize the cages can be determined based on the throughput capacity of the equipment and the amount of redundancy desired for back-up.

Equipment manufacturers should be consulted to clarify the throughput capacity of various types of equipment and equipment options. Only then can the architectural and engineering requirements for the cage sanitation area be established. Architectural requirements will include the physical space required for installing, servicing and using the equipment, including overhead and door-swing space, the depth of mounting pits required for floor loading equipment, the amount of operational space required on both the soiled and clean sides, etc. Engineering requirements will include power, water, wastewater, steam, ventilation and, in some cases, data ports, all of which must be carefully coordinated with the equipment manufacturer. For example, tunnel washers require direct connection to an exhaust air duct and cage and rack washers include an option for connecting to an exhaust air duct, while ceiling-mounted exhaust hoods are required above each door of cage and rack washers as well as autoclaves. All of this will impact the size of dedicated exhaust air system required for the cage sanitation area (see Chapter 34 in this book for details). In addition, codes in some jurisdictions may require a specific temperature and/or pH neutralization of wastewater from

cage-washers. Inadequate hot water temperature and steam supply are the most common reasons for washers failing to reach an adequate water temperature. Steam-to-water heat exchangers should be used for heating water. Direct steam injection into the water should never be used unless it is clean steam.

1. *Cage-Washers*

There are two basic types of cage-washers commonly used in research animal facilities: batch washers and tunnel washers, also called belt or conveyor washers. Most facilities will have both types. Figure 31-1 is a schematic of a cage sanitation facility illustrating a facility with two cage-and-rack washers and one tunnel washer. Figure 31-2 is a picture of the soiled side of a cage sanitation area with one tunnel washer and one cage-and-rack washer.

a. Batch Washers

Batch washers perform all cleaning cycles within a single chamber without moving the article being washed. Soiled equipment is loaded into the washing chamber, the door(s) is (are) closed and the load is sprayed on all sides with large volumes of hot water under high pressure through a series of selected detergent/rinse cycles, after which the cleaned and sanitized items are removed. The smaller batch washers are generally referred to as cabinet washers (Figure 31-3) and the larger ones as cage-and-rack washers (Figure 31-4).

A typical chamber size for a cabinet washer may be 48″ (122 cm) wide × 31″ (79 cm) high × 34″ (86 cm) deep with the floor of the washer chamber being several feet off the floor. Cabinet washers can clean any size cage that fits inside the chamber, including a small number of rodent cages at a time and small parts such as water bottles and feeders.

Cage-and-rack washers are so named because they are large enough to accommodate one or more cage racks. Small items such as shoebox rodent cages, feeders, water bottles, etc., can also be washed in cage-and-rack washers with the aid of cage-wash racks and optional water bottle washing attachments. Cage-and-rack washers are typically floor-loading, being mounted in a pit to make the floor of the washing chamber

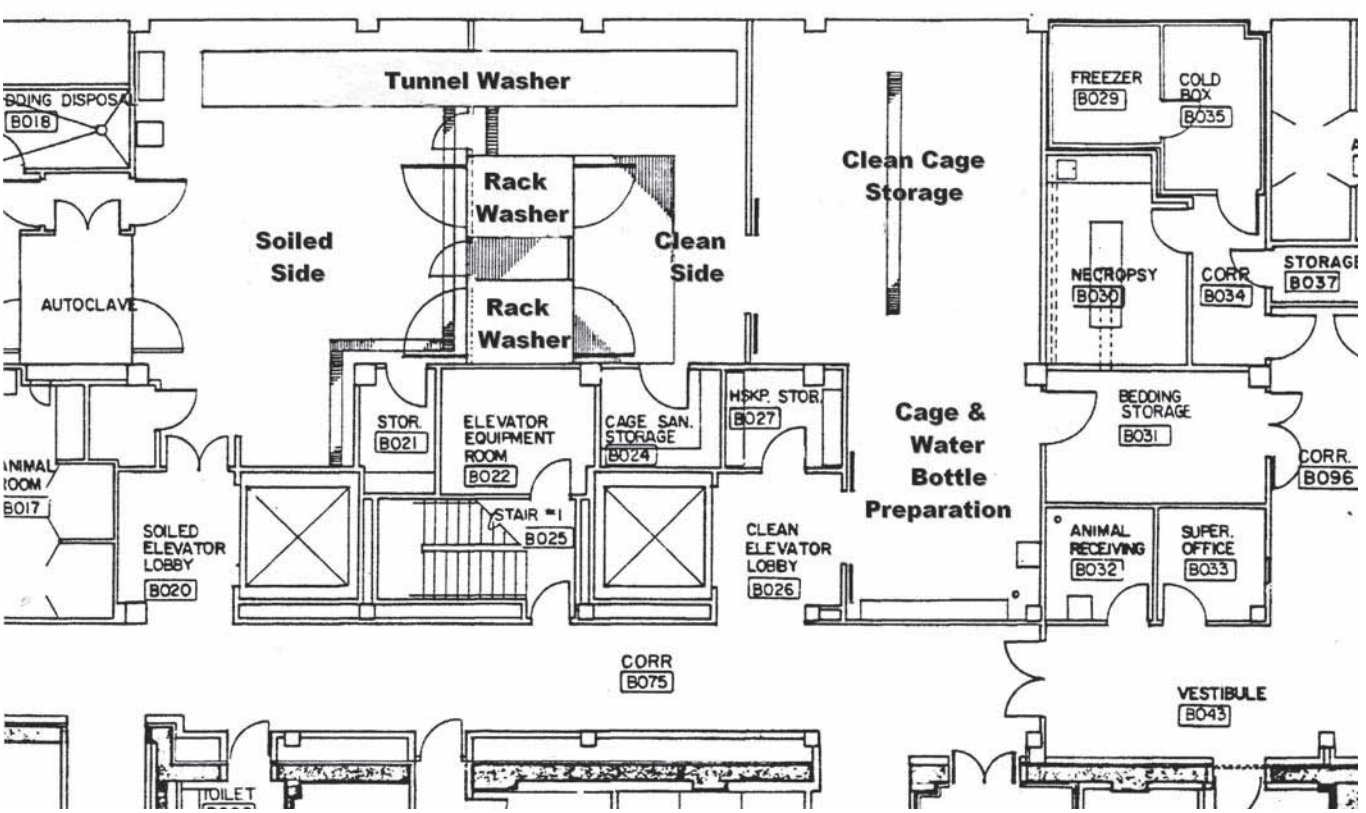

Fig. 31-1 Cage sanitation area. This schematic illustrates a cage sanitation area equipped with two cage-and-rack washers and an ~12-m (~40′) tunnel washer assembly that includes the tunnel washer along with a dryer, bedding dispenser, and collection conveyor. Between the rack washers is a mechanical area for servicing both rack washers that is entered from the soiled side. All the mechanical components of the tunnel washer can also be serviced from the soiled side. To facilitate controlling dust generate by the bedding dispenser (even with a dust collector attached) and cleaning the clean side of cage-wash, there is a wall with an automatic sliding door separating it from the clean cage storage and preparation room. The floor loading pass-through autoclave on the left side of the cage sanitation area leads from a biocontainment area to the soiled side of the cage sanitation area.

Fig. 31-2 Tunnel and rack-washers.
View from the soiled side of the cage sanitation area showing a tunnel washer and rack-washer side by side in a 5.2-m (17') wide room.

Fig. 31-3 Cabinet washer.
This is a single-door cabinet washer. The tank on the side of the washer is a cold-water heat exchanger for cooling the discharge water before it is gravity fed into the sanitary sewer system.

Fig. 31-4 Rack-washers.
Clean side of the cage sanitation area showing three side-by-side pit-mounted pass-through cage-and-rack washers. The open door illustrates that the floor of the washers is level with the room floor. Also visible inside the rack-washer are the spinning spray manifolds. There is a grate-covered pit in front of each rack-washer. Hose reels are mounted in the ceiling of the room.

level with the room floor so that cages and cage racks may be easily rolled into the washing chamber (Figure 31-5). When a pit is not possible, a so-called "pit-less" cage-and-rack washer with a side tank in place of the bottom sump could be considered. These still require a relatively modest loading ramp, and space must be available for the side-mounted tank. To avert ergonomic and safety hazards, loading ramps should be avoided when possible; when this is not possible, they should not be higher than several inches. Chamber sizes vary greatly from those that hold only a single cage rack to those that hold two cage racks end to end, or even ones that hold four cage racks at a time, two wide by two deep. Meticulous attention should be given to load sizes being contemplated to make certain the cage-and-rack washer will accommodate the largest cages or cage racks that will be used in the facility. An all too common error when planning a facility is to focus on the height of animal room doors that will be required to accommodate especially tall equipment (e.g., primate cages or ventilated rack) but neglect to make certain that all the doors in the path from the dock to the animal rooms to the cage sanitation area are tall enough. The most commonly overlooked doors are the cage-and-rack washer doors and elevator doors, if applicable. A good rule of thumb is to make the washer door height no less than the height of the tallest animal room door, assuming that anything that would need to be washed would also have to be taken in and out of an animal room.

Cage-and-rack washers use very large volumes of water for each batch. The default design for batch washers is to use fresh water for each phase of a wash cycle except for the final rinse water, which is saved and used as the pre-rinse water for

Fig. 31-5 Rack washer.
This is a pit-mounted, pass-through rack washer with a wire basket wash-rack that can be used for washing rodent cages and any paraphernalia that will fit into the basket. Special racks for washing-cage pans are also available. Visible inside the rack washer is the oscillating spray manifold.

the next load. However, most manufactures offer an option for storing water in a side tank or tanks. If there are two tanks, one will be used for storing alkaline detergent wash water and another for storing acidified wash water until they are used for subsequent batches. This not only saves water and energy, it also decreases the use of chemicals. Originally, electromechanical timers were used to control cycles, but most modern batch washers are controlled digitally with microprocessors that offer greater flexibility by allowing for a variety of pre-programmed wash and rinse cycles, depending on the type of equipment being cleaned and sanitized. A single cycle may include the following phases: pre-rinse, acid detergent wash followed by a rinse, alkaline detergent wash followed by a rinse, and then a final rinse. The control system can drop or add phases and define the run time for each phase. Depending on the phases chosen and the length of each, a load can take between 20 and 30 minutes, including loading and unloading time.

Pass-through cage-washers with two doors are the standard for the industry because they minimize opportunities for cross-contamination by providing separation of soiled and clean cages. If a single-door washer is chosen, the facility design should include two separate rooms adjacent to the cage-wash room; one for prepping the cages for the washer (including dumping bedding) and one for storing clean cages. Neither of these activities should be done in the cage-wash room equipped with a single-door washer. Essential safety features include switches that automatically de-energize the washer (i.e., turn off both power and steam) if a door is open while the washer is operating. Additionally, there must be a means of de-energizing the washer and opening a door from inside the chamber should someone accidentally be trapped there.

One of many options available is a barrier wall flange that will help seal off the clean side of the cage sanitation area from the soiled side. The washer piping, pumps and valves are typically located on one side of the washer. These may be left exposed, but should preferably be either enclosed inside a stainless-steel cabinet with doors provided as part of the cage-washer, or enclosed inside a "service room" located alongside the washer or between two adjacent cage-and-rack washers that share a "service room" (Figure 31-1). Regardless of which option is chosen, the layout of the washing area should allow for all mechanical maintenance to be done from the soiled side of the cage sanitation area.

Rack washers offer the most flexibility for washing different types and sizes of equipment. If a facility is to have only one cage-washer, with rare exceptions it should be a cage-and-rack washer. A small facility may function adequately with a cabinet washer so long as the size limitations and operational inefficiencies of a cabinet washer are considered to be acceptable compromises.

b. Tunnel/Conveyor Washers

Tunnel/conveyor washers (Figure 31-6) are also commonly used in research animal facilities, especially ones that house large numbers of rodents in shoebox cages and/or many pieces of small equipment such as pans, feeders, flooring and cage inserts, etc. Facilities with a very large number of such cages may require two or more tunnel washers (Figure 31-7). Items to be cleaned and sanitized are placed on a conveyor belt that moves through a tunnel that typically is divided into four sections by virtue of four sets of independently operating fixed-spray manifolds located below and above the load being transported through the tunnel. The four sections are pre-rinse, recirculating detergent wash, recirculating rinse, and final rinse. In some washers, the recirculating rinse water is used for pre-rinse, which is then discarded, and the final rinse water flows into the recirculating rinse water to freshen it. Often, a hot air dryer, an automatic bedding dispenser and a stainless-steel roller conveyor are added at the discharge end of the tunnel washer. Tunnel washers come in a variety of sizes, and can be readily customized to sizes suitable for the animal facility requirements. A typical fully outfitted tunnel washer may

Fig. 31-6 Tunnel washer.
(a) View of tunnel washer from clean side of the cage sanitation area looking through open door into soiled side.
(b) View of a tunnel washer from the soiled side. Note the inward slant of the vinyl curtain at the inlet of the tunnel washer. The tunnel washer chamber is connected to the dedicated cage sanitation area exhaust system, creating a negative pressure inside the chamber that keeps steam from escaping the chamber. Too much room air-flow through the washer chamber can cool the wash/rinse water and impede reaching the desired temperature.

be 40′–44′ (12.2–13.4 m) long, consisting of the following sections: a 15′ (4.6-m) washer/rinse section; an 18″ (46-cm) load and unload extensions; a 6′–8′ (1.8- to 2.4-m) dryer; a 6′–8′ (1.8- to 2.4-m′) bedding dispenser (Figure 31-8); and a 10′ (3-m) roller conveyor to collect cages at the end of the conveyor belt. The width and speed of the conveyor determines the washing capacity. The conveyor belt may be any width. Common widths are between 30″ and 48″ (76 cm and 122 cm). A typical operating speed for the conveyor in a tunnel washer the length of the one described above is 3′ (91 cm) per minute. The longer the washing tunnel, the faster the conveyor belt can run while still providing the same amount of exposure time in each section. Useful options include controls that prevent operation if the water temperature does not meet or exceed a

Fig. 31-7 Tunnel washers.
View from clean side of cage-wash showing the discharge ends of three side-by-side tunnel washers.

Fig. 31-8 Bedding dispenser.
View from clean side of cage-wash showing the discharge end of a tunnel washer, an automatic bedding dispenser, and a roller collection conveyor. Note that the conveyor for the bedding dispenser is lower than that of the tunnel washer. As the shoebox cages, which are washed with the open face down, fall to the lower conveyor, they automatically turn over. The stainless-steel duct works above the discharge conveyor, and attached to the bedding dispenser is a dust collector. Figure 31-20 illustrates a different type of automatic bedding dispenser that is used with robotic systems.

set point, and a sensor switch at the end of the discharge conveyor that automatically shuts off the conveyor when a washed item reaches the end of the discharge roller conveyor.

c. Indexing Tunnel Washers

A third, less commonly used, type of cage-washer is an indexing washer, which provides physical separations between each of the various wash and rinse sections. The conveyor

stops to expose the load for a period of time in each section (see Figure 31-15, below). Index washers may be either cage-and-rack washers or tunnel washers. Indexing tunnel washers are sometimes used in combination with robots for loading and unloading the conveyor. In the case of indexing rack washers, the racks are typically pulled through the washer by a cable attached to the rack or employ mechanical lifts to move the cages through the different sections of the indexing tunnel washers. Indexing washers have not been used extensively in the US except with robots. Major advantages of the indexing tunnel washers include the use of less chemicals, water and steam, which can rapidly generate the return on investment in such a machine. Index tunnel washers may, however, have a lower through-put than standard tunnel washers.

While cage-washer manufacturers use similar basic approaches for their batch and tunnel washer designs, there are some significant differences – e.g., spinning spray headers versus oscillating spray headers for cage and rack washers, and mechanical versus water pressure balance for holding equipment down on the conveyor of a tunnel washer. In addition, each manufacturer offers a variety of optional features. Those unfamiliar with cage-washing equipment and equipment manufactures will do well to carefully study the various features and options of multiple manufactures to determine which is best for a given facility.

2. *Bedding Disposals*

Moving soiled bedding from the cage to a final disposal location can be a major logistical and labor-intensive challenge. The most common method is to manually dump the bedding from the cage into a container (e.g., a plastic bag) and transport the container to a disposal container (dumpster) outside the animal facility, in which it is transported to its final disposal location – usually a landfill or an incinerator. The only significant commonly used improvement in this basic manual dumping method has been the use of special bedding disposal cabinets that use mass airflow to draw dust away from the operator dumping the bedding inside the cabinet. They may either be fixed (Figure 31-9a) or mobile (Figure 31-9b). These units use either a vacuum assisted up- and/or down-draft or a HEPA filtered down-draft principle in their design, to capture airborne particulates, aerosols and allergens. The engineering, construction and special design features of the devices' vacuum and power requirements must be given careful consideration to allow realization of their full operational potential. These types of bedding dumping stations provide a safer work environment for personnel, and are rapidly becoming standard equipment in most animal facilities. They are especially useful, even essential, for dumping from bedding cages containing known carcinogens or toxic chemicals. They may also be linked to a cage-emptying robot, thus giving greater manpower savings, safety, and cage-wash throughput advantages (Terpeluk *et al*., 2000).

Fig. 31-9 Bedding dumping stations.

(a) A bedding dumping station attached to the feed end of a tunnel washer. The dumping station is enclosed on the sides with polycarbonate panels. At the top is an air exhaust vent. At the bottom is a bedding collection hopper attached to a vacuum collection system (see Figure 31-12). In addition, the tunnel washer is under negative pressure that serves to draw from the room across the hopper. Bedding is dumped from the cages into the hopper through a course grate and then passed onto the tunnel washer belt.

(b) Side view of a mobile bedding dumping station facing the load end of a tunnel washer. The dumping station uses a HEPA filtered high-velocity mass air displacement back-draft to draw bedding dust away from the operator. Bedding is dumped inside off trash containers or plastic bags for disposal. Both units are designed to draw airborne particles away from the operator dumping soiled bedding from cages. Figure 31-19 shows an automatic bedding bagging system as part of an automated bedding handling system.

Many different strategies have been tried to reduce the intensity of labor required to perform the essential task of removing soiled bedding from the facility, but none has come to dominate. If local codes allow, disposal units that dump the bedding directly into the sanitary sewer system are probably most efficient (Figure 31-10). Both grinder and hammer mill types with a hopper and auger have been used successfully. Drain-line blockage can be avoided by properly sizing the drains (6" diameter) and by directing wastewater from the

Fig. 31-10 Bedding disposal unit.

Across from the load end of a tunnel washer and next to a wall-mounted utility sink is a bedding disposal unit. This disposal unit feeds bedding from a collection hopper via an auger to a hammer mill for grinding the bedding before disposing of it into the sanitary sewage system. This is a reliable and most convenient way of disposing of soiled bedding when local codes permit. This unit can be fitted with a similar dust-collection system as used in the bedding dumping station illustrated in Figure 31-9(b).

Fig. 31-11 Bedding disposal.

This is the other end of the bedding collection system illustrated in Figure 31-9(a). The vacuum mechanism is located in the structure above the dumpster where the bedding is collected before being haled off to a dump site or an incinerator.

cage-and-rack washer past the discharge line to the disposal unit to carry off the bedding. Another commonly used disposal strategy includes various types of vacuum systems that transport the soiled bedding from a bedding collection hopper in the soiled side of cage-wash to a bulk disposal receptacle outside the facility (Figure 31-11). Figure 31-19 (see below) illustrates a system that automatically bags the soiled bedding as part of an automated bedding handling system. Another strategy is to transport the bedding from a collection hopper in the cage sanitation area to a bulk disposal receptacle outside the building as a water-based slurry. Before dumping the bedding into the disposal receptacle, the water is separated from the bedding and is recirculated to transport more bedding. New strategies are constantly being developed and tried.

3. *Bedding Dispensers*

Many different types of mechanical bedding dispensing strategies have been designed. Ones that fill one or two handheld shoebox rodent cages at a time are available but have not been widely accepted, perhaps because they are not significantly faster or more convenient than the old reliable handheld scoop method. For facilities with a large number of bedded rodent cages, bedding dispensers attached to the tunnel washer have been widely used (Figure 31-8). Such dispensers have a conveyor in line with but at a lower level than the tunnel washer conveyor, so that as cages fall onto the bedding dispenser conveyor they are flipped over and filled with bedding as the conveyor takes them through the dispenser. A dryer at the end of the tunnel washer is nearly always desirable, but especially so when an automatic bedding dispenser is used since cages do not have time to air-dry before the bedding is added. Even with the most dust-free bedding, this type of dispenser generates a significant amount of dust, much of which can be collected with a vacuum attached to the dispenser. When this type of dispenser is used, it is advantageous to separate the clean side of cage-wash from the clean cage storage, to contain bedding dust in as small and easily cleaned area as possible (see Figure 31-1).

4. *Bottle Cleaners and Fillers*

The animal watering strategy to be used is another of the many important decisions to be made in the programming phase of the planning process, since it will greatly impact facility design and equipment requirements. There are multiple strategies for efficiently delivering clean water to laboratory animals and for maintaining the ever-increasing standards for the quality of water provided to laboratory animals (Lempken, 1991; Novak, 1999). Water bottles and bowls continue to be a common means of providing water to research animals, but automatic watering systems are also commonly used for all species, including rodents. Depending on the species housed, a facility will often use a combination of bowls, bottles and automatic watering. See Chapter 32 in this book for information regarding automatic watering and water treatment systems.

When planning and designing facilities that will use large numbers of water bottles, it is critical to plan carefully the logistics and equipment for handling, sanitizing and filling water bottles. For example, a transgenic/knockout (TG/KO) mouse breeding facility designed for 10,000 cages will need to process a little more than 10,000 × ~16-oz (500-ml) water bottles per week. The number of bottles processed each

Fig. 31-12 Water bottle filler.
This is a view from the clean side of cage-wash showing the discharge end of a tunnel washer dedicated to washing water bottles contained in stainless-steel cases. The cases are fed onto the roller conveyor with a water bottle filling manifold that fills bottles a case at a time. The water bottle filling is a manual process.

Fig. 31-13 Water bottle sipper tube cleaner.
This is a self-contained mobile unit dedicated to sanitizing sipper tubes. Note the eye wash, which is an essential safety feature of each room in the cage sanitation area where chemicals are to be used.

week may be reduced by using ~32-oz (1-l) bottles, but the additional weight of the larger water-filled bottles potentially exacerbates the ergonomic and safety issues inherent in using water bottles. Watering bottles are usually glass or polycarbonate plastic with neoprene corks and stainless-steel sipper tubes. Some bottles deliver water through a hole in the side of the bottle or in the bottle top. Water bottle processing, including emptying, cleaning, filling and transporting, is facilitated by handling the bottles in stainless-steel wire cases divided into compartments that hold one bottle per compartment. Bottles may be cleaned and sanitized in cabinet washers, cage-and-rack washers with an optional bottle filler attachment, or tunnel washers. In some cases, tunnel washers dedicated to washing water bottles may be a cost-effective option (Figure 31-12). The choice may depend on the number of bottles to be processed weekly. Water bottle filling stations configured to fill a full case of water bottles at a time are essential. Dedicated equipment for sanitizing water sipper tubes is available (Figure 31-13). Autoclaving sipper tubes is also an option. Many facilities also autoclave the bottle and water for rodents housed under barrier conditions. Water bottles are usually stored and filled in the clean cage storage and set-up area. In facilities that process a large number of bottles, it may be useful to provide a separate room for storing and filling them. One option for supplying water bottles to a barrier facility is to autoclave empty bottles and sipper tubes into the barrier and then fill the bottles inside the barrier with water, e.g., acidified reverse osmosis (RO) water (see Chapter 32). This eliminates the long liquid cycle required for autoclaving water into the barrier (see Chapter 24).

III. AUTOMATED CAGE SANITATION EQUIPMENT

A. Robotic Cage-Washing and Waste Disposal Systems

Robotic cage-washing and handling systems have advanced in the design and operational states, allowing them to be cost-effective and reliable for use in modern laboratory animal facilities. These systems significantly reduce the number of daily manipulations of caging and accessories performed by humans. Other benefits include reduced exposure to allergens and better safety performance. Moreover, ergonomic and other safety performance metrics are improved through the use of robotic systems (Klein *et al*., 1999; Terpeluk *et al*., 2001). Anecdotally, staff morale and retention rates are improved because staff members previously working in non-automated work now have the opportunity to be redeployed to more meaningful and challenging work, thereby creating more engaging jobs in the animal facility. Some of the challenges to installation are offset by careful planning and meticulous attention to engineering and fabrication requirements before the installation of the robotic systems on site. Working out issues and problems at the site of manufacture in factory acceptance testing (FAT) not only saves time but also reduces overall costs and improves cycle times for the project. Unique challenges, such as how to handle removal of wet or clumped bedding, use of irradiated bedding, or retrofitting equipment into existing building layouts with existing utilities, can often be worked out in advance, thus saving time and money (Terpeluk *et al*., 2001).

Fig. 31-14 Robotic cage cleaning.
Dirty-side robot emptying soiled rodent shoebox caging.

Fig. 31-15 Indexing tunnel washer.
Note retracting panels above machine to create closed sections of tunnel washer.

Fig. 31-16 Robotic cage cleaning.
Clean side robot filling sanitized rodent boxes with bedding and placing them on a conveyor.

The robotic systems for cage-washing, clean bedding handling and waste removal consist of multiple elements or functional modules to complete each task in a cage-washing process. These include use of a dirty- or soiled-side robotic unit to empty soiled cages, a device to macerate or strain clumps of bedding (e.g., a rotary sieve), a vacuum-assisted dumping station, an indexing tunnel-type cage-washer, a clean-side robot linked to a bedding dispenser, and a conveyor system. Indexing tunnel washers are used to coordinate belt movement with the time it takes for the robot to load a section of the belt. In addition, indexing washers allow for conservation of utilities and cage-washing chemicals, which also contributes to operational cost savings. These devices are all shown in Figures 31-14–31-20. The use of automated robotic systems alters work flow for both personnel and equipment, as well as traffic patterns within an animal facility, and therefore careful review of work processes and facilities' layout and design should be undertaken. Often, with revision of the facility design and work processes, significant innovations in design and economics of construction can be realized (Klein *et al*., 1999).

B. Semi-Automated Bedding Dispensers

These units are often permanently located in the clean side of a cage-wash area. Their design employs a hopper-type delivery unit controlled by electronic sensors to deliver a pre-set weight or portion of bedding to shoebox-type caging. They can

Fig. 31-17 Rotary sieve unit.
A large rotary sieve used to macerate soiled rodent bedding to facilitate waste handling.

Fig. 31-18 Vacuum system for removing soiled bedding.
Large filters in unit minimize dust and allergens during removal.

Fig. 31-19 Waste bedding bagger.
Large hoppers used to bag soiled bedding for disposal as a completely closed system.

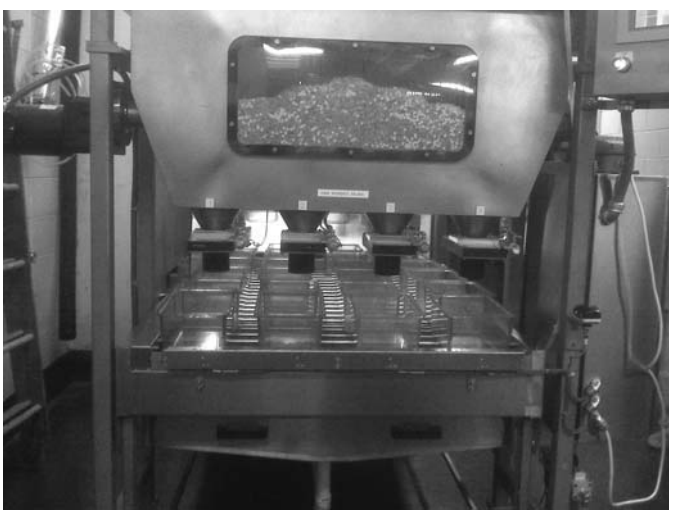

Fig. 31-20 Automated bedding dispenser.
Courtesy of R. Tolwani, Rockefeller University.

either be supplied with clean caging using a robot, or individual personnel can place clean cages in the dispenser manually if the return on investment or business case does not warrant purchasing a robot. An example of such a device is shown in Figure 31-20. Like the bedding dump units, the bedding dispensers help to minimize dust and airborne particulates as they often are designed to filter out dust and aerosols from bedding materials being dispensed. Another advantage of these robotic units is that they eliminate ergonomic/repetitive motion injuries that may result from individual persons manually filling large quantities of rodent boxes on a long-term basis.

C. Automated Bottle Fillers

These devices, like the bedding dump units and the bedding dispensers, offer tremendous advantages in labor savings, but

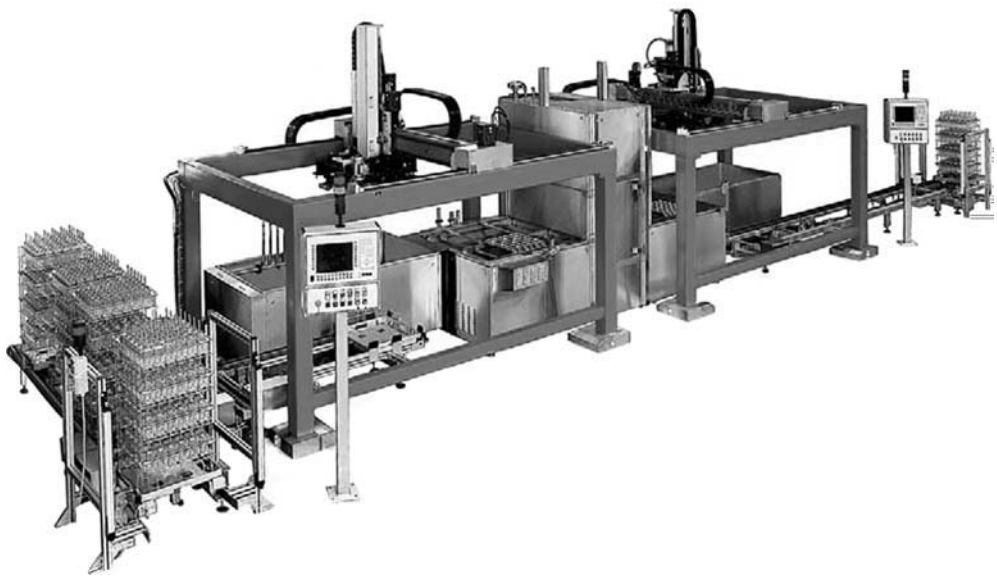

Fig. 31-21 Automated water bottle filler for rodents. Courtesy of Tecniplast.

also in avoiding ergonomic, repetitive-motion injuries to staff members. An important feature of automated bottle fillers is that they fill bottles uniformly and consistently, and minimize water contamination. Their installation may require special utilities and safety engineering, which increases cost; however, the labor and operational savings justify purchase and installation costs. An example of such a device is shown in Figure 31-21.

IV. STERILIZATION EQUIPMENT

Sterilization involves the destruction of all microbial life. The primary method of sterilization employed in animal facilities involves using steam under pressure in autoclaves at temperatures in the range of 250°F (121°C) to 270°F (132°C). Autoclaves are routinely used in research animal facilities to sterilize cages and supplies required for housing rodents under barrier conditions (see Chapter 24), equipment and supplies contaminated with biohazardous agents (see Chapter 25), and surgical instruments and supplies (Chapter 19). With rare exceptions, every animal facility requires at least one autoclave; most will require at least two, and some three or more, depending upon the size, layout and functions performed within the animal facility.

The location, number and size of the autoclaves required for a facility should be documented during the programming phase of the project and, as with cage sanitation equipment, this will require calculating the autoclave throughput volume that will be required. If rodent micro-isolator cages are to be autoclaved, a critical factor in determining the required autoclave capacities, in addition to the number of cages to be autoclaved, is the animal husbandry standard operating procedures to be followed – in particular, whether or not the cages will be autoclaved stacked according to component parts, or fully assembled with the filter lid in place on top of the cage bottom. Obviously, the latter requires significantly more autoclave capacity, but it also reduces the requirement for handling the parts in the animal room. This helps to keep in-room labor and disruption to a minimum, and decreases the opportunities for cross-contamination. In addition, autoclaving soiled cages intact reduces potential contamination of the environment while soiled cages are being transported to the soiled side of cage-wash (see Chapter 24 for a detailed discussion of this subject).

The location or locations of the autoclave(s) depends on how they will be used, how many autoclaves will be installed, and, to a large degree, the operational philosophy of the planning team. There are two basic choices; central or distributive. A central arrangement may involve having a double-door pass-through autoclave located between the soiled and clean sides of the cage sanitation area so that it can be used for decontaminating items taken out of biocontainment as well as for autoclaving cages and supplies to be taken into a rodent barrier. This requires that the items coming from a biocontainment room be wrapped or otherwise enclosed or covered to protect the environment during transport between the animal room and the autoclave, and the same for items being transported from the autoclave to a barrier room. The wrapping and unwrapping process is labor-intensive. A distributive arrangement involves having multiple autoclaves located at the site where they are required to meet a specific need – e.g., rodent barrier areas, biocontainment areas and surgery areas. The most efficient way to maintain both barrier and containment

conditions is the distributive approach in which the autoclave is an integral part of the parameter of a dedicated barrier and/or containment area, so that items can be autoclaved either into or out of the area, thus eliminating the need to wrap or otherwise protect items to be autoclaved. Barrier and containment areas designed in this way, can be operated at little more labor cost than conventional facilities. Whether or not the additional autoclaves that may be required for the distributive approach make this method cost-effective as compared to the more labor-intensive central approach depends on the volume of materials to be autoclaved. Regarding the location of autoclaves for ABSL3 biocontainment, the following is a quotation from *Biosafety in Microbiological and Biomedical Laboratories* (*BMBL*), 5th edition (CDC/NIH 2007):

> An autoclave is available which is convenient to the animal rooms where the biohazard is contained. The autoclave is utilized to decontaminate infectious materials and waste before moving it to the other areas of the facility. If not convenient to areas where infectious materials and/or animals are housed or are manipulated, special practices should be developed for transport of infectious materials designated alternate location/s within the facility.

In other words, ABSL3 containment standards do not require an autoclave as an integral part of the containment area; however, such an arrangement clearly enhances the containment effectiveness and operational efficiency. The same can be applied to ABSL2 containment.

The size of the autoclaves required will depend on the anticipated volume of materials to be autoclaved in the facility. As the use of rodents (mainly mice) has increased dramatically, the number of cages used in research animal facilities, combined with the husbandry practice known as "micro-isolator caging systems" which involves autoclaving cages and supplies, has led to the autoclave volume requirements for animal facilities also increasing dramatically. Many older animal facilities in operation today are equipped with autoclaves that have a chamber size of 24″ (61 cm) wide by 36″ (91 cm) high by 48″–60″ (122–152 cm) deep (Figure 31-22). At the time the facilities were planned, this was considered a large size for an autoclave. Unfortunately, such autoclaves today provide inadequate capacity for the average facility. Today, a "large" autoclave for an animal facility may have a chamber size of 62″ (158 cm) wide × 84″ (213 cm) high × 84″ (213 cm) deep (Figure 31-23).

Just as important to operational efficiency is the labor required for loading and unloading autoclaves. The smaller autoclave described in the previous paragraph typically requires a special load rack dedicated to the autoclave that must be loaded and unloaded each cycle, plus a special cart for rolling the load rack into and out of the autoclave (two carts if it is a double-door pass-through autoclave) that takes up floor space (Figure 31-22). Regardless of the size, autoclaves to be used for routinely autoclaving cages and other animal-care supplies should be pit mounted and floor loading (Figure 31-23) to achieve maximum operational efficiency. This allows cage loads to be rolled into and out of the autoclave on the same carts used to transport the cages from the clean side of cage-wash to the animal room, and then the same carts can be used to return soiled cages to the soiled side of cage-wash. This approach is not only more ergonomically sound; it also greatly reduces the labor costs of loading and unloading autoclaves. See Chapter 24 for a detailed discussion of this subject. In addition, a pit-mounted floor loading autoclave allows cage racks and other miscellaneous rolling equipment to be easily loaded into the autoclave. In cases where pit mounting is not an option, a low-profile platform lift with a modest ramp can be used to raise autoclave load carts or other rolling equipment from the floor to the level of the bottom of the autoclave chamber and back to the floor. Of course, this is still more labor-intensive than loading a pit-mounted autoclave. Figure 31-24 illustrates another option for loading autoclaves that are not pit mounted. The primary disadvantage of this option is that

Fig. 31-22 Autoclave.
This is a double-door autoclave with a 61-cm (24″) wide by 91-cm (36″) high by 152-cm (60″) deep chamber that is used for autoclaving rodent cages and other animal-care related supplies. In front of the autoclave is a cart, and on the cart is an autoclave load rack. A cart is required on both sides of the autoclave to hold the load rack outside of the chamber as the cages are loaded onto and off the load rack.

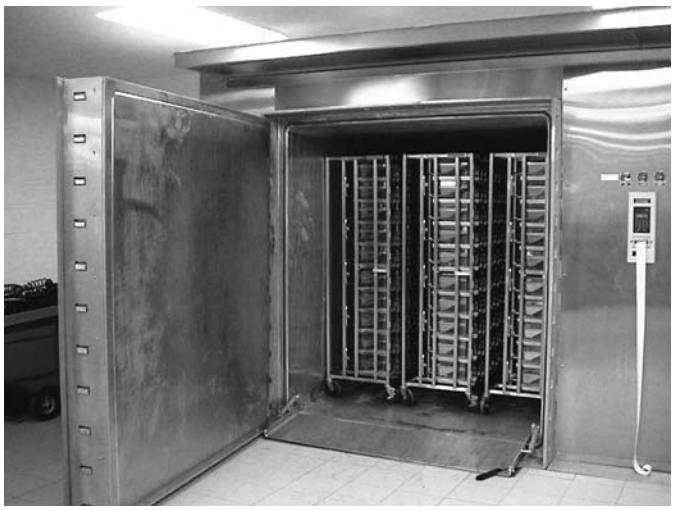

Fig. 31-23 Autoclave.

This is a pass-through, pit-mounted, floor loading autoclave with a chamber size of 158-cm (62″) wide × 213-cm (84″) deep × 213-cm (84″) high. Inside the chamber are three single-sided mouse racks with cages completely set up ready to use. The facility was programmed to allow for clean and soiled cages to be transported and autoclaved on the same racks holding the cages in the animal room in order to keep cage-handling at a minimum. Note the pull-down ramp required to bridge the gap between the room floor and the floor of the autoclave chamber. This bridge is typically not required with sliding doors.

Fig. 31-24 Autoclave.

This autoclave could not be pit-mounted, so a special handling system was designed to facilitate loading the cage transport carts into and out of the autoclave without having to transfer the cages from a transport cart on to an autoclave load rack to a transport cart and then back to a transport cart.

it is not as efficient or as versatile as a floor loading autoclave, since it is limited to items that will fit on the autoclave cart.

High-vacuum autoclaves are strongly recommended because they significantly improve both sterilization effectiveness (especially for bulk supplies such as feed and bedding) and efficiency, as compared with gravity autoclaves. Most modern autoclaves have digital control systems that produce reports for each load. Hinged or sliding doors are often an option, especially for the larger autoclaves, and which to choose may depend on the physical layout of the area where the autoclave is to be installed. Overhead sliding doors are an attractive option for saving floor space when overhead space is available, such as in facilities with high ceilings or designed with interstitial mechanical space (see Chapter 13). The skid for the autoclaves can also be located in the interstitial space. As compared with hinged doors, sliding doors have the advantage of decreasing the gap between the autoclave chamber floor and the facility floor, eliminating the need for a bridge.

To avoid exposing animals to chemical additives typically found in boiler-generated steam, clean steam should be considered for autoclaves used to sterilize animal cages, feed and bedding (see Chapter 34). Stainless-steel piping should be used with clean steam, as clean steam will rust black iron pipe, resulting in rust contamination in the autoclave chamber.

As with cage-washers, the use of wall flanges designed to create a sealed barrier between the two sides of a pass-through autoclave is an available option. In a barrier facility, the wall flange would be located to place the autoclave skid with the mechanical and plumbing components outside of the barrier. In a containment facility, the wall flange should be located so that the autoclave skid is inside the containment area. This is to assure that air and liquids from the autoclave chamber are contained inside the containment area.

Ethylene oxide sterilization is rarely required for animal husbandry support, but is frequently required for supporting experimental surgery programs. Ethylene oxide is a carcinogen; therefore, detailed safety requirements governing the installation of ethylene oxide sterilization equipment have been established and must be followed. Newer technology provides sterilization of hard surfaces using hydrogen peroxide or gaseous chlorine dioxide in sealed chambers.

V. SECURITY AND CONTROLLED ACCESS

The great value of research animals combined with increasingly militant activities opposing the use of animals for biomedical research and safety testing requires that all research animal facilities have a sound security program. The first priority is to strengthen the perimeter by controlling access to the facility. Access points should be kept to a minimum, and all those that will be routinely used should be equipped with microprocessor-controlled security access devices managed by the institution's security service. Given the importance of security for research animal facilities, security systems that use biometrics (e.g., thumb or palm prints, retinal scans, voice recognition, etc.) are highly recommended. Closed circuit TV monitoring and recording at access points should also be considered.

For management reasons, controlling access within the animal facility can be considered an issue separate from security. While it does provide additional security, its primary benefit is as a management tool to protect animal health and the integrity of the research by controlling and monitoring access to animal housing rooms and areas. No one should have access to an animal room or isolated areas – e.g., barrier, biohazard, primate, quarantine, etc. – without prior approval. Since it is the animal facility management that must approve who has access to a room or area, this system is most conveniently managed by animal facility personnel. Key lock systems are marginally manageable when a small number of people require access. When a large number of people in a high turnover population require access, a key lock system is unmanageable and thus ineffective. Effective access control can best be achieved with a microprocessor-controlled security system. Some individuals, especially the animal-care staff, will require frequent access to some rooms or areas throughout the day; therefore, careful consideration should be given to the selection of a convenient-to-use personal identification system.

VI. FIRE ALARMS AND SPRINKLERS

The issue of fire alarms and sprinklers in an animal facility is a difficult one to address, partly because such issues are controlled by local fire codes and partly because there is no ideal solution. All options that provide the necessary safety for personnel may negatively impact the animal's environment and thus the animal's physiological response to experimental variables. Careful use of professional judgment is necessary. Ideally, there should be no fire sprinklers or fire alarms in animal rooms or loud alarms outside the animal rooms that can be heard in the animal rooms. Some local jurisdictions will exempt animal rooms from sprinkler requirements on the grounds that minimal flammable materials are present there. Fire alarms are more of a concern because they are routinely tested, guaranteeing periodic interruption of the animal's environment. There currently are two options available for fire alarms; strobe light alarms and "silent alarms" that operate at a frequency below the 400-Hz level heard by rats and mice (e.g., at 370 Hz) but within a range heard by humans (see Chapter 7). Neither is ideal. Strobe lights have the potential to disrupt the animal's circadian rhythm, trigger photogenic seizures in certain strains of animals, and adversely affect personnel. In addition, the silent alarms are within hearing range of other species. There have been reports of problems in getting local officials to accept the "silent"/low-frequency alarms. At this time, there is no research to clarify which option has the least negative ramifications. Clearly, the typical audible fire alarm must not be used in animal rooms, and their use outside animal rooms should be limited to areas where they cannot be heard inside an animal room.

VII. SUMMARY

There are many diverse equipment requirements for modern research animal facilities, generated by the type of research and the animal species involved, and much of this equipment involves sanitizing and sterilizing animal cages and supplies. Tight timelines and schedules, coupled with high costs of either renovation or construction, drive the need for flexibility in design of animal facilities. The use of carefully planned and selected equipment, including the automated/robotic equipment recently introduced into research animal facilities, can minimize renovation or construction costs while reducing operational costs, thus permitting an optimal return on investment. More important than financial aspects is maintaining the high standards of animal health, animal welfare and personnel safety.

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Chapter 32

Plumbing: Special Considerations

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I. INTRODUCTION

Plumbing (from *plumbum*, the Latin word for the element lead, which was the material used in the early construction of water pipes) is a key component in the design, construction and operation of animal research facilities. At its most basic function, plumbing carries both fresh water and steam to the facility, and wastewater away from the facility. However, plumbing for vivarium purposes also involves the provision of drinking water for research animals (especially if via automated watering systems), the modification and recirculation of water for housing aquatic animals, the specialized design and construction of cage sanitation facilities, and the use of distribution systems for steam and other specialized fluids, such as detergents.

The remainder of this introductory section highlights the importance of water quality to research animal studies, the regulations and guidelines that affect the installation of plumbing in animal housing facilities, the characteristics of water as modified for drinking by the general public, and the drinking water options available to animals. The second section of the chapter focuses on the design and installation of general plumbing systems and cage sanitation facilities, while the third section details the plumbing issues associated with automated watering systems. The provision of water for aquatic species is discussed briefly in the fourth section, concentrating on the provision of water to the animal housing room; the chapter in this book on facilities for aquatic species will describe the systems available for supplying individual housing tanks. The final section notes plumbing design considerations in association with disaster planning, and means to help temper the impact of disasters.

A. Importance of Water Quality

In the design of research animal facilities, one of the most important considerations is to minimize, whenever possible, any environmental variations. Inconsistent environmental parameters can unintentionally alter the results of the scientific study being undertaken. In facility design, this concern is often addressed with regard to providing consistency in temperature and lighting; it has been well documented how variations in room lighting durations or intensities can affect the outcome of animal-based research projects (Small and Deitrich, 2007). However, this concept of consistency should also apply to the quality of water that is supplied to the animal housing facility.

The importance of water quality is most apparent in housing fish and aquatic amphibians (*Xenopus* spp.), as variations in temperature, acidity and hardness, and the presence of toxic levels of chlorine, ammonium or nitrite, can significantly impact the experimentation being conducted (Browne *et al*., 2007; Densmore and Green, 2007; Green, 2007). Variations in the quality of drinking water provided to mammals can also affect research results and animal health (Hermann *et al*., 1982; Sparks *et al*., 2002). The quality of water in a facility can also minimize the effectiveness of sanitation efforts, or cause accelerated deterioration of equipment. Some facilities have had to install water-softening systems in order to prevent calcium deposits from rapidly developing within cage-washing machinery (G. Keller, 2007, personal communication).

B. Regulations and Guidelines

The primary regulation that governs the quality of water provided for human consumption in the United States is the federal Safe Drinking Water Act (SDWA), originally passed by Congress in 1974, and amended in 1986 and 1996. The primary objective of the SDWA is "to protect against both naturally-occurring and man-made contaminants that may be found in the drinking water" (EPA, 2005). The US Environmental Protection Agency (EPA) is charged with setting the national standards for drinking water, and coordinating with state governments and local water systems to ensure compliance with these standards. The standards are essentially a list of potential contaminants and their allowable maximum contaminant levels.

For design and installation of water piping in the United States, the primary reference guidelines are plumbing and construction codes. Unfortunately, there are multiple codes in existence within the United States, each endorsed by a different organization or association. For example, the National Standard Plumbing Code (NSPC) was published by the Plumbing-Heating-Cooling Contractors National Association; the Uniform Plumbing Code (UPC) was developed by the International Association of Plumbing and Mechanical Officials; the National Plumbing Code (NPC) was written by Building Officials and Code Administrators International; and the Standard Plumbing Code (SPC) was developed by the Southern Building Code Congress International. Many of these codes have regional support – for example, the SPC is used primarily in the southeastern United States, whereas the UPC is used in the western states. There are efforts to coordinate these "regional" codes into one national code.

With regard to guidelines specific to plumbing and animal research facilities, the *Guide for the Care and Use of Laboratory Animals* (the *Guide*; ILAR, 1996) and the USDA regulations pursuant to the Animal Welfare Act are the documents of note. In the *Guide*, the quality of drinking water is addressed in Chapter 2 ("Animal Environment, Housing, and Management"). It states that animals "should have access to potable uncontaminated drinking water according to their particular requirements," and notes that water quality and hardness will vary with location. The *Guide* further mentions that periodic monitoring of water quality and potential contamination may be warranted, and that if water treatments are necessary, consideration as to potential effects on experimental results (e.g., potential physiologic alterations, changes in bacterial microflora) is necessary. Guidelines for plumbing itself are noted in Chapter 4 ("Physical Plant"), and only in association with drainage: "Drainpipes should be at least 4 in (10.2 cm) in diameter. In some areas, such as dog kennels and farm animal facilities, larger drain pipes are recommended."

The USDA regulations address water and plumbing issues in Part 3 – Standards, which is subdivided along species lines into six subparts: A – Dogs and Cats, B – Guinea Pigs and Hamsters, C – Rabbits, D – Non-human Primates, E – Marine Mammals and F – Warmblooded Animals Other Than (*those animals specified in Subparts A–E*). Within each Subpart, issues of "water and electric power," "drainage and waste disposal," and "washroom facilities" are noted in the "Housing facilities, general" section under the "Facilities and Operating Standards" supersection, and provision and quality of drinking water

are in the "Watering" section under the "Animal Health and Husbandry Standards" supersection. For dogs, cats and non-human primates, regulations state that facilities "must provide adequate running potable water [to meet] the [animals'] drinking needs, for cleaning, and for carrying out other husbandry requirements." For guinea pigs, hamsters, rabbits and the other warmblooded animals, the regulations simply state that "adequate potable water shall be available." As would be expected, the regulations for marine mammals are more descriptive in the "Water and power supply" section, which requires written contingency plans for emergency sources of water, and in the "Water quality" section, which addresses coliform bacterial and salinity standards as well as the frequency of water sampling for coliform counts (weekly) and assays of pH and chemical additives (daily).

The "drainage and waste disposal" sections state that housing facilities must be equipped with drainage systems "that are constructed and operated so that animal waste and water are rapidly eliminated and animals stay dry." The drainage system must minimize vermin and insect infestation, odors, and potential disease hazards, and must be properly constructed, installed and maintained. Closed drainage systems must have traps to prevent the backflow of waste gases and sewage into the animal housing room. "Standing puddles of water in animal enclosures must be drained or mopped up so that the animals stay dry." The use of sump or settlement ponds is permitted, but they must be located "far enough away from the animal area of the housing facility to prevent odors, diseases, pests, and vermin infestation." With regard to "washroom facilities," the subparts basically state that washing facilities for animal caretakers ("such as washrooms, basins, sinks, or showers") "must be provided" where dogs, cats or non-human primates are housed, and "shall be provided" where guinea pigs, hamsters, rabbits, marine mammals and other warmblooded species are housed.

C. Definitions and Characteristics of Water Sources and Treatments

The quality and characteristics of water provided to animal housing facilities are as divergent as the types of facilities themselves. Responsible individuals at each facility will need to have a solid understanding of the condition of the water that is supplied centrally to the building in order to know what modifications, controls and monitoring systems are necessary to ensure that the quality of water remains fairly consistent. A chemical analysis of the water from the system should be performed to determine the hardness, possible presence of harmful contaminants, the possible corrosiveness of the water, and the tendency of the water to stain fixtures. From this analysis, the need for additional treatment of the water can be determined and the proper equipment selected. Such equipment might include water softeners to prevent scaling of water heaters and cage-wash equipment. Green sand filters for iron removal are also common, depending on the area of the country. Within the animal housing facility, water for animal consumption can be filtered (by several different means and to different degrees) and/or treated (e.g., acidified or chlorinated). Details regarding possible sources of drinking water and on intra-facility methods to modify drinking water are described below.

1. *Source Water*

a. Municipal Water

Most facilities receive water that is supplied and processed by a public water system. Each public system must satisfy the federal requirements for safe drinking water (i.e., the standards pursuant to the SDWA, which identify the allowable maximum contaminant levels), as well as any additional state or local mandates. Although the standards are based on federal law, the actual disinfection and control measures used to adhere to those standards are at the discretion of local governmental agencies. As such, the quality and composition of public drinking water will vary from system to system, but will still meet federal requirements.

Typical processes for water purification include coagulation, flocculation and sedimentation (a three-stage process to remove large particulates); filtration; disinfection by some manner of chlorination; and fluoridation for the prevention of tooth decay in the national populace. The method of chlorination is very important, as some methods (e.g., use of chlorine gas) enable laboratories to use aeration as a means to dechlorinate for housing aquatic species, whereas other methods (such as the addition of monochloramine) require specialized additional treatment at the aquatic animal facility in order to dechlorinate.

An understanding of the expected municipal levels of chlorine should be determined prior to any hyperchlorination steps attempted by the facility. Some municipalities may chlorinate up to a concentration of 3 ppm. While this is, in fact, below the chlorine levels recommended for prophylaxis in laboratory animals (see "Hypercholorinated water", below), its presence in the municipal drinking water will decrease the amount of supplemental chlorine needed to achieve the desired concentration within the facility.

b. Well Water

Some facilities have direct access to water from local aquifers, or "well water." This water is not conditioned in any way for human consumption or use, and so it is typically free from chlorine and fluoride additives. As such, it has advantages as a water source for housing aquatic species. The actual elemental content of this water, however, will vary from location to location, and therefore it is necessary to completely analyze well water to determine its appropriateness for aquatic animal

housing and/or drinking water. There are no federal regulations for private wells; the criteria based on the SDWA only apply to public drinking water systems. Private wells may, however, be subject to state or local requirements that are typically less restrictive. Since the consistency and quality of well water may be questionable, it needs to be analyzed frequently to determine suitability for drinking or housing aquatic species.

2. *Water Treatment*

a. Acidified Water

One measure used to reduce the level of microbes present in the drinking water of research animals is to acidify the water. Acidification has been demonstrated to greatly reduce bacterial populations and to prolong the health and/or lives of animals undergoing specific experimental procedures. Acidification has typically been accomplished by the addition of hydrochloric acid, although the use of sulfuric acid has also been verified (Hall *et al*., 1980). The target pH is typically 2.0–2.5, with lower pH ranges being associated with palatability problems, and higher pH ranges with incomplete disinfection.

b. Hyperchlorinated Water

The other classic method of reducing microbial populations in drinking water is to hyperchlorinate the water. Sodium hypochlorite is typically added to the drinking water so that chlorine concentrations of 12–20 ppm are achieved (Homberger *et al*., 1993; McPherson, 1963; Bywater and Kellett, 1977).

c. Distilled Water

Distillation is the process of separating organic and inorganic contaminants from water through a combination of evaporation, cooling and condensation.

d. Deionized Water

Deionization is a method for the removal of inorganic impurities; it does *not* remove organic or cellular material and may, in fact, enhance bacterial growth within a water system (Newell, 1980). The process removes all ionized minerals and salts from water by a two-phase ion-exchange procedure. First, a cation-exchange resin removes positively charged ions in exchange for a chemically equivalent amount of hydrogen ions; second, an anion-exchange resin removes negatively charged ions for a chemically equivalent amount of hydroxide ions. The hydrogen and hydroxide ions introduced in this process unite to form water molecules.

e. Reverse Osmosis (RO) Water

This water treatment process is effective for the removal of inorganic material, as well as microbes and associated toxins. Reverse osmosis removes undesirable materials from water by using pressure to force the water molecules to flow through a semi-permeable membrane in the reverse direction (i.e., from the concentrated solution to the dilute solution), rather than from the dilute to the concentrated, as in natural osmosis. RO removes ionized salts, colloids, and organic molecules down to a molecular weight of 100.

f. Ultraviolet (UV) Light-Treated Water

Ultraviolet light has been known to kill bacteria after brief exposure. As such, it has been used in association with decontamination of water in drinking systems. It is rarely used alone, however, as it has several disadvantages. First, it does not remove ions or organic material, as do some of the other purification methods (e.g., RO water). Second, it kills bacteria but does not remove the dead bacteria or its liberated toxins. Third, it is not completely efficient, and depends on a contact time that may be difficult to achieve with flowing water.

g. Medicated Water

Occasionally, antibiotics or other medications are added to the drinking water as a means of administration to the research animals. This is typically associated with a very specific subset of the colony animals that is being treated for an illness (therapeutically or prophylactically) or receiving the antibiotic as a promoter for targeted gene transcription. As such, it is most often used with water bottle systems and not introduced into the automated watering system (although this has been done at poultry and livestock production facilities). As with acidified and chlorinated water, it is important to change the water bottles when the additive becomes inactivated so that the animals are receiving a proper amount. Palatability is always an issue with medicated drinking water, so close observation is needed at the initiation of any new medicated water protocols to ensure that the animals are drinking and not becoming dehydrated. It is also important to know if the compound becomes inactivated by light; opaque or wrapped bottles can be used in these instances to delay the breakdown of the additive compound.

3. *Other Water Quality Definitions*

a. Greywater

Greywater, or sullage, is water collected from drains and reprocessed within the facility for use in cleaning operations (not for consumption). In essence, the practice within some cage-washing machinery of collecting drain water from a rinse cycle for use in the next washing cycle is an effective use of greywater. Typically, greywater is obtained from drained fixtures such as showers, sinks and washing machines, but not toilets. Unfortunately, most facilities collect the greywater discharge along with the more contaminated effluent (blackwater),

making it impossible to use the greywater for any recycling purpose. For this reason, extreme forethought must be employed in order to segregate greywater drainage from true sewage drains. It would then be possible to plumb together the drains from greywater fixtures in a facility, provide simple water treatment, and use this greywater for secondary functions, such as flushing floor or trench drains (see "Floor drain/trench flushing" section below).

II. GENERAL PLUMBING

A. Hot and Cold Water Systems

Hot and cold water systems for animal facilities need to be reliable in order to ensure that operation of the facility is uninterrupted. Water supply to the animal facility should be redundant with dual feeds. If supplied from a municipal or campus water source, a sectional valve needs to separate the two feeds at the site main to ensure isolation of one feed. In addition to redundancy of supply, additional future capacity in the water supply should be planned to allow for expansion of the facility or changes in operation (e.g., introduction of a large number of aquatic species).

Water supplied to the animal facility should be segregated from the normal domestic water used for toilets, showers and human consumption, to ensure that there is no cross-contamination to/from human watering systems. This can be accomplished by the use of a reduced pressure zone backflow preventer to ensure maximum protection. If a segregated system is not feasible, then the system should be carefully designed with appropriate vacuum breakers and backflow preventers to assure that water from the animal facility does not contaminate the remainder of the building system.

A water flow test should be performed to determine the available pressure and flow rate from the water source for the building. It is especially important to obtain flow tests from different time periods during the year, since public water usage typically varies over the course of the year. If the water source is from a municipal system, discussion with the local utility is important to determine whether there are any known possible distribution problems or renovations in the area that may affect the flows and pressures available in the future. Some equipment items, such as cage-washers and autoclaves, may have higher pressure requirements, and as such may need water-pressure boosting systems. For small facilities, it may be possible to provide individual booster pumps at specific pieces of equipment to avoid high pressures at other fixtures within the building. It is very important at the early stages of a project to review the available and required water pressures to determine the need for pressure-boosting equipment and the layout of the piping system.

Layout of the hot and cold water distribution should minimize the amount of piping above the holding rooms to limit damage and disruption of studies. Each room should have its own valved supply to allow for minimal disruption of studies for maintenance and renovation. All valves and piping must be clearly labeled to identify the spaces served. Distribution should be from an interstitial level to provide the most protection and to limit disruption to the research studies. This also limits the need for maintenance personnel to access the holding room areas, and makes renovation easier since valves and piping are more accessible. If an interstice is not suitable, then supply should be from the corridor directly outside the holding room. Valves must be readily accessible above the corridor ceiling for safety and ease of maintenance.

For larger facilities, water mains should be looped on each floor with sectional valves to allow for isolation of parts of the floor to minimize disruption for maintenance or renovation. Consideration should be given to dual risers to allow for dual feeds to floors and minimize shutdowns for maintenance.

Hot water within the animal facility is primarily used for cage and room wash-down to maintain a clean and hygienic facility and ensure continued animal health. Typical water temperature for a whole building system for this use is 140°F. This temperature will limit the growth of *Legionella pneumophila* bacteria within the hot water system. For sanitizing equipment, a temperature of 180°F is recommended (ILAR, 1996). This temperature increase can be accomplished by the addition of facility steam at a branch point near the equipment, or by the use of individual booster heaters incorporated into the equipment.

In addition to wash-down uses, hot water is also needed for hand-washing sinks. These sinks should be provided in each animal holding and procedure room to enable the animal handlers to clean their hands as they move from room to room within the facility, and thus prevent possible cross-contamination. It is important to note that for hand-washing the hot water temperature should be limited to 110°F to avoid scalding. This can be accomplished by providing a separate 110°F hot-water recirculation system for such fixtures, or providing local tempering valves that lower the hot water temperature for each point-of-use or for a collection of adjacent fixtures (such as in locker rooms). Providing mixing valves at each individual fixture that reduce and limit hot water temperature to 110°F can achieve this goal as well.

Production of hot water can be accomplished by various methods. It is important to note that the cage-wash operation can vary based upon the status of the research studies. At times the cage-wash may operate for 8–12 hours continuously, so the hot water system must deliver hot water reliably during this period. If it fails to do so, then validation of the sanitation of the cages cannot be assured and then the cages will need to be washed again. Due to this requirement, instantaneous steam-to-water heaters are usually best suited to meet these needs. The downside to this is that it must be ensured that the steam supply can keep up with the hot water heater demand.

The piping material most commonly used for hot and cold water systems is copper tubing with lead-free soldered joints.

Hot and cold water piping should be insulated for energy conservation and condensation protection, respectively.

Cold water piping should be sized to limit the maximum velocity to 8 feet per second (fps). Hot water piping should be sized to limit maximum velocity to 5 fps for 140°F or less, and to 3 fps for higher temperatures. Point-of-use hot water fixtures should be within 25 feet of the recirculated main in order to maintain temperature. Pipe sizes should be calculated utilizing water supply fixture units and Hunter's Curve (an algorithm that estimates flow in gallons per minute – gpm – based on the type of building and the number of relative "fixture units" within the facility), then adjusted for large equipment demands.

If containment holding room spaces (such as ABSL3) are designed, then additional consideration for isolating plumbing services to rooms must be accommodated. Check-valves or backflow preventers for each water service entering each space may be required by commissioners or accrediting agencies. Hot water should not be recirculated out of the contained space. If the distance from the point-of-use hot water fixture to the recirculated main exceeds 25 feet, then an alternative means to recirculation must be accommodated. Heat tracing or in-room recirculation and booster heating may need to be considered.

Consideration should be given to sustainability with the system designs. Methods of water and energy conservation should be investigated with equipment vendors. Energy conservation by reclaiming waste heat from the equipment waste discharges should be considered to pre-heat the incoming cold water to the hot water system.

B. Drainage Systems

Waste from animal facilities is predominately animal waste and water from cleaning operations. This type of waste can be directed to the building's sanitary sewer system. The waste system from the animal facility should be segregated from the normal domestic waste from toilets, showers and human use areas to ensure that odors or cross-contaminants are not released to human occupancy sites. The separate drainage systems can be combined either just within or outside the building.

Most holding rooms in an animal facility will require floor or trench drains to aid in cleaning. Holding rooms for small animals like rodents and rabbits may be cleaned and disinfected by wiping down or mopping; as such, floor drains are not absolutely required for these rooms. However, maximum flexibility for holding spaces, and the potential for leaking issues with automated watering systems, suggests that floor drains should be provided in all animal housing rooms, although they may be capped based on infrequent use. The location of floor drains within the housing rooms needs to be evaluated based upon the room layout and standard cleaning procedures. Drains located to the side of the room (near a wall) make it easier to direct the water and waste to them. Trench trains along both sides of the room are usually the easiest to clean. Another option is to locate a capped circular drain beneath the sink. Drains must be located at the low points of the floor, and the floors should be sloped downward toward the drains. Slopes of floors should be between 1/8- and 1/4-inch per foot. The pitch within trenches should follow a similar slope.

Selection of drain types, materials and grate sizes needs to be evaluated to allow for waste to flow through and not impede the rolling of cages and carts through the room. Durability of the finishes to frequent washing and disinfectants needs to be reviewed to determine longevity. Custom drains, strainers or grates may be required to meet the specific requirements for the facility. Materials for the floor drains include cast iron with nickel-bronze rims and grates, epoxy-coated cast iron, polypropylene, and type 316 stainless steel. Materials for trench drains include poured-in-place concrete, pre-manufactured polymer concrete, fiber-reinforced plastic (FRP), polypropylene, and type 316 stainless steel. Interior finishes of drains should be smooth and free of crevices to assure proper drainage and ease of cleaning.

Drain outlets should have a 4-inch minimum diameter, with 6-inch diameter recommended for handling larger waste and possibly bedding. Drains require strainers by plumbing code, and they need to be selected to allow for waste to flow. Waste piping should slope at 1/4-inch per foot and should be sized for half to two-thirds full flow. The minimum pipe size below grade should be 2 inches, and the minimum pipe size above grade should be 1.5 inches. System demand should be calculated utilizing drainage fixture units and the Hunter's Curve. The minimum design velocity shall be 2 fps to assure scouring and conveyance of solids in the waste.

Piping should be installed in accordance with plumbing codes for gravity drainage. Drains must be vented and have p-traps (pipe curvature that goes below the level of the drain line branch to create a water seal and prevent backflow of waste gases). Vent piping should be sized based upon a positive or negative pressure of a 1-inch water column, as normal plumbing codes dictate. For high containment rooms the p-trap depth needs to be increased from the standard 2 inches to a depth corresponding to the HVAC pressure differential between the supply and exhaust plus an additional 2.5 inches. If this is not done, trap seals will be compromised and odors will be evident within the space.

Pipe material for below-grade piping may be hub and spigot cast iron. Above-grade piping may be hubless cast iron, except for instances in which drainage piping is located above other functional rooms. In these cases, cemented or fused plastic piping systems should be used to ensure that there are no leaks above the room. If disinfectant chemicals or acidic or alkali detergents are used in large quantities, the pipe materials should be evaluated to ensure that they can withstand the chemicals used. Possible treatment of the wastewater should

also be considered if the chemical load might exceed local limitations on wastewater discharge.

Most animals are sensitive to noise, and drainage piping may transmit loud and atypical sounds during heavy wash-down periods. To alleviate this noise transmission, drainage piping above animal holding rooms should be insulated. In addition, light-walled piping, which may transmit or amplify noise in drainage systems, should be avoided for drainage piping above animal holding rooms.

Due to the nature of the wastewater being a mixture of feces and bedding, some facilities incorporate the use of an in-line comminuter ("a machine that shreds or pulverizes solids to make waste treatment easier" – EPA, 2007) or waste grinder to break down the solid waste to manageable particle size. These should be located as close as possible to the waste source to minimize potential blockages. These devices need to be readily accessible for service and maintenance. When plumbing codes permit, some pulverizing bedding disposal units (Garb-el Products Co., Lockport, NY) can be connected directly to the water drainage system. Discharge water from the rack washer can be used as the means to maintain flow and send the pulverized bedding through the draining system (J. Hessler, 2007, personal communication). Due to the bedding and waste, cleanouts should be provided in excess of code requirements to ensure that all segments of the piping system can be cleaned. Cleanouts should be well marked and located to assure easy access. Cleanout covers should be smooth and crevice-free to aid in cleaning the facility.

If it is determined that pH correction or some other pre-release waste treatment needs to be completed within the facility, then the drainage system needs to be designed to accommodate this requirement, as well as the characteristics of the initial waste that warrant the mitigation (e.g., acidity). Comminuting the waste and possibly screening to collect bedding needs to be considered. Avoidance of clogging needs to be considered in the tank and piping design; larger pipe sizes, sloped bottom tanks and/or mixing to aid in keeping particulates in suspension need to be incorporated. Hard piped vents on tanks along with gasketed manways (sealed portals that enable human entry) and mixer seals will aid in alleviating odor problems within the facility.

C. Steam and Steam Condensate Return Systems

Steam piping systems differ from other building utility piping because they actually carry three different fluids: steam, water and air. It is important to know the proportions of these fluids when sizing the steam piping. Steam systems are traditionally classified by steam pressure: low pressure is 0–15 pound-force per square inch (psi), medium pressure is 15–100 psi and high pressure is 100 psi and above. Steam can deliver a large amount of heat as it condenses back into a liquid, and the higher the pressure, the higher the temperature that the steam can deliver. Steam tables identify the temperature, specific volume and heat capacity information at different pressures as a means to determine the size of the system. In sizing steam systems for general heating, steam velocities in the piping should be limited to 4,000–6,000 feet per minute (fpm); for sizing steam systems for process systems (such as cage-washing), higher velocities such as 8,000–12,000 fpm can be used.

The quality of the steam needs to be evaluated with regard to how and where it will be used. General-purpose non-contact steam can be provided from all building steam systems. Steam used for humidification or for injection into sterilizer chambers needs to be clean steam using an RO water source, since any trace chemicals may not be acceptable. This is especially true for autoclaves that will be sterilizing bottled drinking water, as it is important that general-purpose steam contaminants do not affect the drinking water quality.

Pressure reduction needs to be done in one or more stages based upon the turndown ratio (the ratio of the maximum measurable flow rate in the system to its minimum measurable flow rate). Systems used for heating should be sized for 100 percent demand. Process heating systems should be sized for 100 percent for large demands and for 25–50 percent for smaller demands, depending on system size. Allowances should be included for warming up the system.

Piping for steam should be a minimum of schedule-40 wall carbon steel with threaded, flanged or butt-welded joints. Condensate piping should be a minimum of schedule-80 wall. For clean steam systems, stainless-steel piping should be used. Piping should be designed with all necessary offsets, anchors, guides and expansion loops to allow for expansion and contraction without creating stresses and strain. Piping should be sized to maintain the pressure drop between 5 and 10 percent.

Steam traps (devices to remove condensate water from steam lines) should be provided after all equipment using steam. Drip legs with traps should be provided on long steam mains every 200 feet for automatic warm-up systems, and up to 500 feet apart if the steam mains are heated manually. Condensate should freely drain from equipment by gravity without back-pressure. Traps should be sized to allow the system to come up to temperature. Sizing will be based upon the estimated loads, the estimated pressure before the trap, and the back-pressure after the trap. A safety factor (the ratio of breaking strength to load) of 1.2–4 shall be applied, based upon the trap type selected. Some recommendations for installing traps are as follows:

- traps should be located as close as possible to the collection leg;
- lifting the condensate or piping condensate directly to a return line under pressure should be avoided;
- pipe connections to and from the trap should be at least equal to the trap connection size and include full size isolation valves;
- a strainer and blow-down valve should be installed before the trap;

- a test and pressure-relief fitting is recommended downstream of the trap to ensure that the service valves are holding;
- all low points of the steam main (and wherever condensate can collect) should be drained.

D. Distilled/Deionized/Reverse Osmosis Water Systems

Purified water may be required in the procedure and support spaces within an animal facility. The first decision needs to be what water quality is required throughout the facility. The necessary quality will vary based upon the specific use(s) for the purified water.

There are at least four different water quality standards in use in the industry: the College of American Pathologists (CAP), the American Society for Testing and Materials (ASTM), the Clinical and Laboratory Standards Institute (CLSI, formerly NCCLS), and the United States Pharmacopeia (USP). Once a standard is selected, the specific water quality type must be determined. For example, ASTM uses the designations Types I, II, III and IV for the various purities for reagent-grade water. Type I is the highest quality water used for critical applications, like trace element analysis and HPLC, and Type IV is the lowest quality, used for less critical applications like glassware rinsing.

Purified water can be produced by a central system and distributed through the building, or at the point-of-use, or by a combination of these methods. It is not unusual to have a central system producing Type IV water which is distributed to all use points, and then each individual use point has a polishing unit which gives a higher grade of water (Type I, II or III) if required.

A variety of different combinations of equipment can be combined to produce purified water to meet the various quality standards. Some standards specifically spell out what process may be used to produce the water. The need for storage of the water depends on the size of the system and the amount of water used. Small systems may be able to use cartridge filters and no storage. Larger systems may need to use larger media filters and require storage. As there is a wide variety of equipment currently available relating to water purification, with continually advancing technology, this chapter will address a typical "average" system.

A typical purified water system features several different stages of treatment. Usually, domestic water is delivered to the inlet of the treatment system at 77°F and then passed through a multimedia filter to remove particulate and biological substances. The 77°F temperature is considered the ideal temperature for the most effective production of reverse osmosis (RO) water. The filtered water is then passed through a water softener to remove hardness (minerals) from the water, and through a 3-μm filter to capture any resin that might pass from the softener bed. A means for chlorine removal is then provided, such as chemical injection or activated carbon, followed by a 5-μm filter to capture any additional particulates. After this, the water enters the RO unit itself, which pressurizes the water and forces it through a membrane that prevents any impurities from passing. This pure water is then directed to a storage tank, which is usually sized to hold 1 day's worth of water.

From the storage tank, water is drawn through pumps and may be passed through further polishing with a deionization (DI) system to produce higher-quality water. Newer technology that has come into use over the past 10 years uses electrodeionization, which electrifies the process of regeneration of the exchange resin. The water is then passed through an ultraviolet (UV) light to sterilize it. A final 0.2-μm filter is usually provided to collect any resin from the DI process or degenerated biological material from the UV treatment. This water is then distributed through a piping system to the points-of-use.

The piping system for the purified water can be dead-ended at the terminal point-of-use or recirculated back to the storage tank. A dead-ended system may allow bacterial growth within the piping due to water stagnation. A recirculated system keeps the water moving at between 3 and 5 feet per second to create a scouring action in the piping to reduce bacterial growth. If a recirculating system is used, the terminal points-of-use that branch off of the recirculated main need to be kept as short as possible to prevent local stagnation.

To estimate the volume of purified water that the system must produce daily, a load of 10 gallons per day per sink outlet can be used as a figure for general water usage. For specialized equipment that uses the purified water, the demand must be investigated based upon the specific requirements of the equipment and the facility. For design flow rates, sink outlets should be estimated at 1–2 gallons per minute (gpm) and equipment outlets estimated at 5 gpm, unless a higher flow rate is required by the specific equipment to be served. The pipe sizing for the purified water system should be based upon an average velocity of 3–5 fps. The minimum design pressure at outlets should be 20 psi. If point-of-use polishing units are to be used, it must be verified that the water supply flow and pressure requirements for the primary system satisfy the requirements for the secondary purification system(s).

There is a wide variety of choices for pipe materials for purified water distribution; these need to be evaluated based upon the specific application. Water quality, sanitation method, operating pressures and operating temperatures, as well as market availability and contractor experience, need to be evaluated in addition to material cost. Piping system materials that have been selected for distribution of purified water include polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), natural or pigmented polypropylene (PP), polyvinylidene fluoride (PVDF), and types 304 or 316 stainless steel. PVC and CPVC pipes are joined with solvent-cemented socket joints; these solvents may contribute extractable contaminants and the joints can be locations for the development of bacterial biofilm. PVC and CPVC can only be chemically sanitized, but they are the least expensive and may be best suitable for

less pure water. Polypropylene is the most widely used material, and can be joined using heat-fusion socket joints, heat-fusion butt joints, infra-red heat-fusion butt joints, or beadless crevice-free infra-red heat-fusion joints. This last joint is the smoothest type, resulting in the least surface area for possible bacterial growth. However, PP must also be chemically sanitized. PVDF has the same joining methods as polypropylene, but can be heat sanitized as well as chemically sanitized.

Stainless steel has been widely used in the process industry, mainly for its ability to be heat sanitized and its durability against abuse. Stainless steel has a variety of interior surface finishes, from the most common 180-grit mechanical polishing up to the mirror-like polishes of 20 Ra (roughness average) or less. There is no one material that is best for all applications, but polypropylene and stainless steel are the most popular.

The need for validation of the system needs to be determined as soon as possible. The design documentation and record-keeping during fabrication need to be included in the construction process. Finally, complex purified water treatment systems should be instrumented with malfunction alarms as well so that staff can be alerted to problems with production or flow.

E. Wash-Down Systems

1. *For Rack Washing*

In cage-wash areas, animal housing racks and larger accessories (e.g., transport cages) may be pre-washed in a dedicated area of the room in order to remove large debris prior to sanitization in the automated rack washer. The pre-wash area should have a sloped floor with a trench drain along the back wall to collect the water and waste. Sometimes this area may have a grating above the sloped floor to allow a flat surface on which to work.

A hot water hose station should be located nearby to flush the rack with hot water. The hose stations should operate at a pressure range of 50–80 psi with a flow rate of between 5 and 8 gpm. This hose station may have the ability to spray detergent with the water to aid in removing debris. A dedicated detergent spraying system is an alternative; its use would be followed by a water-only rinse to remove the detergent and debris residue. A separate hot water heater and plumbing distribution system for wash-down areas and animal holding room hose bibs (see below) enables the hot water temperature to be higher than that used for general use, such as for hand-washing sinks.

2. *For Holding Rooms*

For cleaning the animal housing rooms, copious amounts of water are often needed. Fixed hose stations with a mixing valve using hot and cold water, or steam and cold water, may be provided to wash down the rooms, depending on the animals housed and the cleaning procedures the owner wishes to follow. Depending on the specific needs (as detailed below), these hose stations can be supplied from the general water piping systems, or by use of an alternative recirculating hot water piping system that provides water at higher temperatures and pressures.

Holding rooms for larger animals, such as dogs and pigs, usually have hose stations to make cleaning easier. These hose stations can be surface-mounted, recessed, or enclosed in cabinets to have a cleaner appearance. The hose stations should operate at a pressure range of 50–80 psi and flow rate of between 5 and 8 gpm. Standard stations can operate at up to 150 psi, but it should be cautioned that at higher pressures the feces might be aerosolized, possibly exposing the workers to pathogenic bacteria.

Holding rooms for larger animals like ruminants may require hose stations that need higher flow and/or pressure. High-volume hose stations with flows of up to 50 gpm and adjustable spray patterns aid in washing of these larger spaces. High-pressure stations similar to those used in commercial car washes can reach pressures as high as 3,000 psi. These higher pressures aid in cleaning, but worker comfort and safety becomes a concern. At these pressures, the hoses and nozzles become difficult to handle and control. In addition, room finishes may be removed when pressures this high are used, especially if there is any delamination or damage to the finish.

Holding rooms for small animals like mice, rats, guinea pigs or rabbits may be cleaned and disinfected by wiping down or mopping. In these rooms, hose stations may not be required.

If two-level cages are used, such as for primates, a wall trough may be required to collect the waste and rinse water from the upper level of caging. The upper level trough is mounted to the wall along with a waterproof wall covering. Common materials to fabricate the trough and wall covering are stainless steel or PVC plastic. These troughs are custom fabricated to suit the room and cage arrangement. The upper trough drains down into the lower trench drain. The lower drain outlet must be sized to allow both levels to drain freely, unless cleaning procedures are set in place to avoid washing both levels at once.

F. Floor Drain/Trench Flushing Systems

Drains within animal facilities are sometimes provided with manual or semi-automatic flushing systems to flush the drains themselves of particulate debris. For floor drains, the drain bodies are manufactured for flushing capability by the addition of an inlet to deliver water just below the rim and grate. A cold water connection is made to this inlet at the drain, and a second connection is made to the associated p-trap. This double connection is used so that as water is flushed to the drain, additional water flows into the trap to ensure carriage of the waste and prevention of sedimentation. Design of the flushing system needs to evaluate the number of drains flushing at once to ensure that the system can handle the required flow rate.

Trench drains can also be provided with flushing systems. Nozzles to provide water to flush the trench are typically situated at the ends of the trench. The nozzles are located either a few inches above the floor, or just below the grate if the trench is deep enough. Flushing nozzles can be as simple as an open pipe nipple or a manufactured nozzle. Nozzles that produce a fine high-pressure spray may aerosolize feces, so they should be avoided. Wide fan-shaped nozzles work best to provide water in a laminar flow without creating a spray mist. The design of the flushing system needs to ensure the required pressure and flow rate for all nozzles flushing is provided. Pipe sizing should account for the number of trenches expected to be flushed simultaneously.

There are a few different ways to control the supply of water for flushing drains. A simple manual ball valve may control the water supply. With a ball valve, a vacuum breaker or backflow preventer must be provided to isolate the water supply from the waste drainage system and prevent contamination of the water supply. Another method is to provide a wall-mounted or recessed flush valve (similar to a toilet flush valve) to supply water for drain flushing. The flush valve can be manually controlled or solenoid activated. Because this type of valve closes quickly, the sudden back-pressure induced upon the flowing water ("water hammer") can result in pipe damage after extended usage. For this reason, specially designed air chambers known as "water hammer arrestors" should be provided in association with these flush valves, typically as a terminal end to the supply water line just past the valve. A third method to control the water supply to flush drains is to provide a concealed solenoid valve that would be operated by a push button located within the holding room. This type of valve would also require a vacuum breaker or backflow preventer to isolate the water supply, as well as a water hammer arrestor.

The duration for which the solenoid valve stays open can be controlled in one of several ways. With the most basic method, depressing the push button controls the valve directly and thus the valve remains open only as long as the button is pushed; this method requires someone to physically be at the location of the button for the entire duration of the flush. Another method uses a push button with an integral timer that can be adjusted to dictate the duration of the flush. This method enables the staff member to perform other tasks once the flush has been initiated. A more technologically complicated method is to link the solenoid into the building management system and thus control the time and duration for which the valve is open (similar to solenoid control for flushing of non-recirculated automated watering systems – see "Non-rcirculating (flushing) system" section, below). This method could also enable the building management system to control the number of drains that are flushing at once.

With increased focus on sustainability, floor and trench drain flush systems are excellent applications for use of rainwater or greywater, since they do not require the use of high-grade (clean) water. Rainwater from the building roof or site can be collected, filtered and disinfected for use in drain flushing. Greywater is wastewater collected from sinks, showers, dishwashers and water coolers. Although ordinarily admixed with true wastewater from toilets, greywater can be collected separately, then filtered and disinfected for use in drain-flushing operations.

G. Detergent Systems

Animal facilities are manpower-intensive operations due to the cleaning operations of the rooms and cages. In some large facilities the operation of the cage-wash is intensive enough to justify the need for a centralized detergent distribution system. These systems usually have bulk detergent tanks with pumps and controls that supply detergent either directly to the wash equipment or to a local day tank, which then supplies the wash equipment. The bulk detergent tanks are typically located in a room near the loading dock of the facility to ease their delivery, although some facilities locate them within the cage-wash facility. The loading dock location limits the movement of detergent drums through the facility, thus reducing labor and increasing safety.

The detergents usually consist of an acid, an alkali, and possibly a neutralizer. Due to the nature of the detergents, a means of pH correction may be required to stay within local pH discharge limits, usually around pH 5–9. The allowable pH limits need to be verified based upon the local requirements.

The distribution system for each detergent consists of a bulk tank, a distribution pump, piping or tubing, and controls. Containment for the bulk tank needs to be considered in the event of a failure or spill. Design of the distribution system also requires consideration of the containment of leaks and protection of personnel. Materials for the distribution system need to be compatible with the detergent used. Flexible plastic tubing is usually used as the primary means for detergent supply, with a rigid plastic secondary containment pipe or conduit enclosing it from the tank to the wash equipment. Routing of the tubing/conduit needs to be designed to enable accessibility for maintenance, investigation of leaks and possible tubing replacement. Controls with these systems monitor the detergent level in the tanks, operate the pumps and interface with wash-equipment controls to activate detergent supply as required. Experienced detergent vendors can often supply this control equipment as a pre-manufactured system. Some experience with detergents is required due to certain nuances with foaming of the detergent, and experience with materials compatibilities must be considered with the pumping and controls associated with these systems.

In addition to having detergent supplied to wash equipment, sometimes dedicated detergent spray systems are provided within the facility. These stations are supplied from a central detergent system and are pressurized for spray application to the spaces. Pipe materials need to be selected to suit the chemicals used at the pressure and temperature delivered.

H. Specialty Systems

Similar to the detergent system, other specialty supply and collection systems may be required for an animal facility. Support laboratories associated with the holding rooms may require the use of liquids like formalin, saline, alcohol or other solvents. If sufficient volumes of these liquids are used, a centralized distribution or waste-collection system may be justified to save labor and increase safety by eliminating the movement of multiple containers through the facility.

These systems need to be custom-engineered and fabricated to suit the particular application. Evaluation of past liquid usage will aid in sizing the storage tank, pump and distribution piping. A process flow diagram (PFD) for determining flows, pressures, and pipe and pump sizing must be prepared to fully ensure that the system will perform adequately. A piping and instrumentation diagram (P&ID) is then prepared, indicating the locations of gauges, sensors and controls.

Careful evaluation of materials selection for the tank, pump, valves and piping needs to be done based upon the specific liquid being transferred. Detailed evaluation of all materials of construction for pumps and valves must be done to ensure reliable operation and safety. The joining method for the piping system needs to be evaluated to ensure a safe system and minimize potential leaks. The need for purity and possible validation needs to be explored. Material finishes, fabrication methods and cleaning procedures need to be evaluated.

The need for secondary containment of the tank and piping must be evaluated based upon the material being transferred. Assessment of the total amount of liquid within the building needs to be evaluated with the maximum volumes allowed by the applicable building code. Separate control areas may be required to limit the allowable volumes within the building.

The system should then have a hazardous operations analysis review to determine whether any hazardous conditions exist and if any additional safeguards need to be added. During this analysis, various "what if?" scenarios are evaluated to determine whether a hazardous situation could result from the failure of a component in the system. Additional safeguards should then be added to prevent such possibilities.

An experienced process equipment fabricator should fabricate the system equipment and controls. It can then be factory fabricated and tested complete with controls to assure equipment functions as planned. The equipment can then be delivered to the site with minimal field piping and wiring. Systems like these must be commissioned during construction to ensure that they operate as designed.

III. DRINKING WATER

A. Water Delivery Systems

The decision regarding how drinking water will be provided within an animal facility is based on multiple factors, including institutional operating practices, space allocation, available budget, and species to be housed in the facility. The options for providing drinking water to animals used in research are bottles, automated watering systems, film bags, or open ware such as troughs, buckets, bowls and crocks (Table 32-1). While open ware has applications in the husbandry of cats, livestock and poultry, bottles are a traditional and widespread form of supplying water to research animals.

TABLE 32-1
Relative Rank Comparison of Water Delivery Systems (as Compared to Bottle)

	AWS	Bottle	Open ware	Packaged water
Species	All	Rodents, rabbits	Large animals	Rodents
Installation cost	↑↑↑	0	0	↑↑
Maintenance cost	↑↑↑	0	0	↑↑
Daily operating costs	↓↓	0	↑	↓
Material handling equipment	↓↓↓	0	0	↓↓
Water quality, initial	0	0	↓	0
Water quality, residual	↑	0	0–↑	?
Ergonomic compatibility	↑↑	0	0	↑
Disease transmission risk	↓	0	0	?
Animal safety	↓	0	0	?

AWS = automated watering system with RO water.
Bottle = water bottle +/− sipper tube, serviced weekly, RO water.
Open ware = crocks, troughs, bowls and the like serviced daily and given municipal tap water.
Packaged water = bagged RO water, serviced every 2 weeks.
↑ = cost, quality or risk is greater than water bottle.
0 = cost, quality or risk is equivalent to water bottle.
↓ = cost, quality or risk is less than water bottle.

1. *Water Bottles*

As compared to other options, water bottles are less expensive to acquire, offer the flexibility of use for multiple species (ranging from mice and songbirds up to non-human primates), and can be used in an array of settings from small facilities to large operations, and from barrier (exclusion) housing to biocontainment. Bottles are also particularly well-suited for oral delivery of medicated fluids (e.g., doxycycline administration to Cre-lox mice, antibiotics to otherwise lethally irradiated rodents) and for accurate monitoring of fluid consumption. Water bottles are discouraged in settings with non-human primates due to the risk of scratch or other injuries to personnel when servicing cage-affixed bottles and encountering aggressive animals. Overall, in circumstances where there is sufficient and competent animal-care staffing, the provision of water via bottles is as safe, and often safer, for the recipient animals than other choices, in terms of encountering floods or risking dehydration (Huerkamp *et al*., 1994).

Water bottles may be manufactured from glass or transparent plastic resins, and are available in a variety of configurations and capacities. The classic means of providing water to small animals

has been via a glass bottle with a rubber, neoprene or equivalent stopper and a stainless-steel sipper tube. Glass bottles are essentially inert, they can be easily autoclaved (empty or filled), and glass resists chemicals and other potentially degrading substances. However, glass bottles are prone to chipping and breakage, especially from dropping. This presents a hazard to personnel, and is also a cause of progressive inventory depletion. Lohmiller and Lipman (1998) reported that autoclaving glass bottles may result in increased silicon concentrations and the formation of silicon crystals under certain circumstances (e.g., increased pH of water, degenerating rubber stoppers).

Bottles made of molded resinous polymers are resistant to breakage from dropping, have varying resistance to heat and chemicals, sometimes have source-to-source and batch-to-batch variability in quality, and vary in cost (Novak and Lamborn, 1998; Novak and Dickinson, 1999). Some of these resins, particularly polyphenylsulfone, may survive 100 or more autoclave cycles (Novak and Dickinson, 1999) and may last 4–5 years under conditions of practical use. Based on warranty returns, polyphenylsulfone implements have a 1 percent failure rate after 24 months of use in a broad spectrum of research institutions (W. Bean, 2003, personal communication).

The general drawbacks to water bottles, however, are numerous. Even with chemical treatment, the microbial content and quality of the water within the bottle drifts over time (Danneman *et al*., 1999). Water bottles must be maintained in a relatively massive inventory, requiring significant space dedicated to storage, and considerable labor must be spent filling, distributing, dumping and cleaning the bottles. Additionally, the handling and management of water bottles has been identified as one of the greatest risks for work-related musculoskeletal injury among animal resources personnel (Georgelos *et al*., 1999). Mechanical automation of water-bottle handling has been achieved by several manufacturers in recent years. The Kronos™ (IWT, Casale Litta (Va), Italy) and AutoCap (Allentown Caging Equipment, Allentown, NJ) systems are, to a considerable extent, automated solutions for handling water bottles in the cage-washing resource. These mechanized systems process hundreds of bottles per hour, and enable significant reductions in manpower and corresponding costs.

The costs for sanitation of bottles alone, including water consumption, detergent and other chemical purchases, cage-washer depreciation and use of electricity, are considerable relative to other options. Beyond cage-wash, water bottles also add a cumbersome element of labor to cage-changing along with all of the accompanying ergonomic considerations for staff who must handle hundreds of bottles and dozens of cases, each weighing 25–30 pounds, on a daily basis in animal housing rooms. Due to breakage and deterioration, water bottles and stoppers must be replaced on a periodic to regular basis. When thermoplastic resins and rubber stoppers deteriorate, the cracks, fissures and holes that develop are difficult to visualize upon regular inspection (Hayes-Klug and VandeWoude, 2000). This deterioration results in leaks that may be difficult to detect and which result in unpredictable but self-contained floods (Hayes-Klug and VandeWoude, 2000). These small floods can be innocuous for adult mice of traditional stocks and strains, but can be lethal for neonates prone to hypothermia, or to brittle genotypes unable to cope with environmental stress. Problems with leaky bottles and stoppers increase as the implements age, making it a challenge for staff to act prospectively (unless all bottles are periodically replaced *en masse*), with the only recourse being the inefficient one of permanently removing bottles from use as they leak.

A complication specific to bottles made of plastic polymers is that some have poor resistance to alkalis and also additives that may be found in steam, such as morpholine (Novak and Lamborn, 1998; Novak and Dickinson, 1999), and encountered consequently during cage-washing and autoclaving. Another potential risk associated with plastic resin bottles is denaturing upon exposure to some experimental drugs or agents. When these resinous polymers deteriorate, they may show any combination of stress cracking, pock marks, loss of gloss, swelling, warping, apparent partial melting, and brittleness (Novak and Dickinson, 1999). Exposure of some materials to alkalis during washing has caused the occult emission of an unintended endocrine disruptor byproduct, bisphenol A (BPA), with subsequent animal exposure (Cohen, 2003; Koehler *et al*., 2003). BPA can also leach into the drinking water from plastic resins, especially as the bottles age (Howdeshell *et al*., 2003).

Most water bottles are used in conjunction with a sipper tube and stopper. In this case, sipper tubes generally are a site of considerable microbiological contamination (Danneman *et al*., 1999) and biofilm formation, and are difficult to sanitize adequately. In the case of rodents, particularly mice, another risk of sipper tubes is that flooding may occur if bedding is pyramided under the sipper, enabling water to be wicked into the cage interior (Hayes-Klug and VandeWoude, 2000). To circumvent the issues of contamination and flooding, bottles may be used without sipper tubes. These so-called "shoulder holder" bottles have a drilled hole on the side facing the cage bottom that permits water drop release by capillary action when the rodent licks at the hole. Bottles of this design may not allow for sufficient water consumption by diabetic rodents or other genotypes with high water demand.

In a field trial of 450-ml water bottles in a breeding colony of pair and trio mated mice, 20 percent of water bottles did not provide sufficient volume to last 2 weeks (Danneman *et al*., 1999). At an operational level, this translates into weekly cage access in order to provide a reliable supply of drinking water. If ventilated caging systems (VCS) are used in the facility, the weekly cage access needed for water bottles negates some of the labor savings/cost advantage of only having to change the VCS cage every 2 weeks. A detailed annual cost analysis done at Emory University showed that it cost 16 percent more to maintain mice in filter top cages with water bottles

than in VCS with an automated watering system (AWS) (L. Morelock-Roy, 2004, personal communication). This can be a difference of almost $300,000 per year in the scenario of a 10,000-cage census, with a *per diem* of $0.50 for VCS with AWS and a *per diem* of $0.58 for VCS with water bottles.

2. *Automated Watering Systems (AWS)*

As an alternative to water bottles, AWS offer the advantage of reducing labor and containing animal-care costs while factoring the ergonomic disadvantages of water bottles out of the animal-care process. Animal-care technicians are freed by AWS from the labor-intensive daily processes of lifting, filling, carting, dumping and storing large numbers of bottles, and can concentrate on providing attentive animal care and support to scientists. As such, these systems are preferred for large animals such as dogs, non-human primates, pigs and rabbits, and are becoming more popular for use with rodents. Where the system is designed for continuous flow or circulation, animals are provided with constant access to water that is of more consistent quality than bottles (Edstrom, 2003). Large-capacity tanks, typically integral to the system, offer the serendipitous benefit of providing a reservoir of emergency water. Likewise, should weather or other circumstances keep personnel out of the workplace, AWS continue to deliver water for days at a time, and beyond when bottle volumes would be exhausted.

Simplistically, AWS involve the circulation of water from a stored and treated/purified source out to animal holding rooms via a header system and circuit of pipes (Edstrom, 2003). At some point(s) before entering the animal holding rooms, the water passes through installed pressure-reducing stations (PRS) where the water pressure is reduced from 40–60 psi to 3–5 psi (Figure 32-1). After exiting appropriate treatment- and pressure-reduction stations, piping enters each room, runs along the walls (usually above rack height), and then penetrates a wall into the next room in sequence. The relatively high positioning is necessary to prevent inadvertent damage from colliding racks or other mobile pieces of equipment (Figure 32-2). In rooms outfitted with mobile racks, pens or cages, the room distribution piping is connected to the units with a quick-disconnect recoil hose (Figure 32-3), which enables the racks to be disconnected from the system so that they can be moved to different rooms or for washing. The piping mounted on each rack, or to a complex of kennels or pens, is termed the *manifold*. A drinking valve ("lixit") is attached to the manifold at each cage position, allowing water to be delivered to the animals in each enclosure. Animals obtain drinking water by biting or licking the stem to divert it from a central position (Edstrom, 2003) – a process analogous to releasing air from an inflatable tire through the valve stem (Figure 32-4).

Fig. 32-1 Pressure-reducing station. The canister at the right within the PRS contains a 5.0 micron particulate filter; the two silver structures on the left and in the center are the valves that control the pressures for normal drinking and for system flushing.
Courtesy of the University of Michigan.

As described in more detail in the "Distribution system options" section below, there are two basic options for AWS distribution: recirculating and non-recirculating (flush). Within both of these options, the recirculation and/or flush can involve only the room distribution piping, or include the rack manifolds as well.

In recirculating systems, unconsumed water returns to a central point for re-treatment (e.g., UV light disinfection, hyperchlorination) and is then continuously pumped through the room distribution lines. In flushing systems, the unconsumed water is periodically drained out of the system by a high-pressure flush of treated or untreated water. The primary advantage of the recirculating system is that it conserves water; this may be especially significant in facilities in which extensive pre-treatment is provided (such as use of RO water for drinking water). It also does not require the multiple solenoids and control systems that the flushing system needs. It does, however, require continual electrical power to operate the circulating pumps, which must be equipped with emergency power. In the event of a power failure, the flushing component of the non-recirculating AWS is suspended, but water is still delivered through the system to the animals by the pressure delivered by the source system.

Regular flushing or continuous circulation is critical for suppression of bacterial proliferation in the manifold and piping systems. Of all the contaminants in the water supply, and regardless of the manner supplied, bacteria are amongst the most difficult to control (Lindsey *et al*., 1991) and even survive in nutrient-depleted, generally inhospitable reverse osmosis water (Favero *et al*., 1975; Payment, 1989). They accomplish this by adhering to a surface and secreting a protective, slimy glycocalyx. Whether in municipal water supply pipelines, bottles, sipper tubes or manifold systems, contaminating bacteria will rapidly attach to any wet surface and form a biofilm (Edstrom, 2003) – *Pseudomonas aeruginosa*, for example, may adhere to electropolished stainless steel within 30 seconds of exposure (Van Haecke *et al*., 1990).

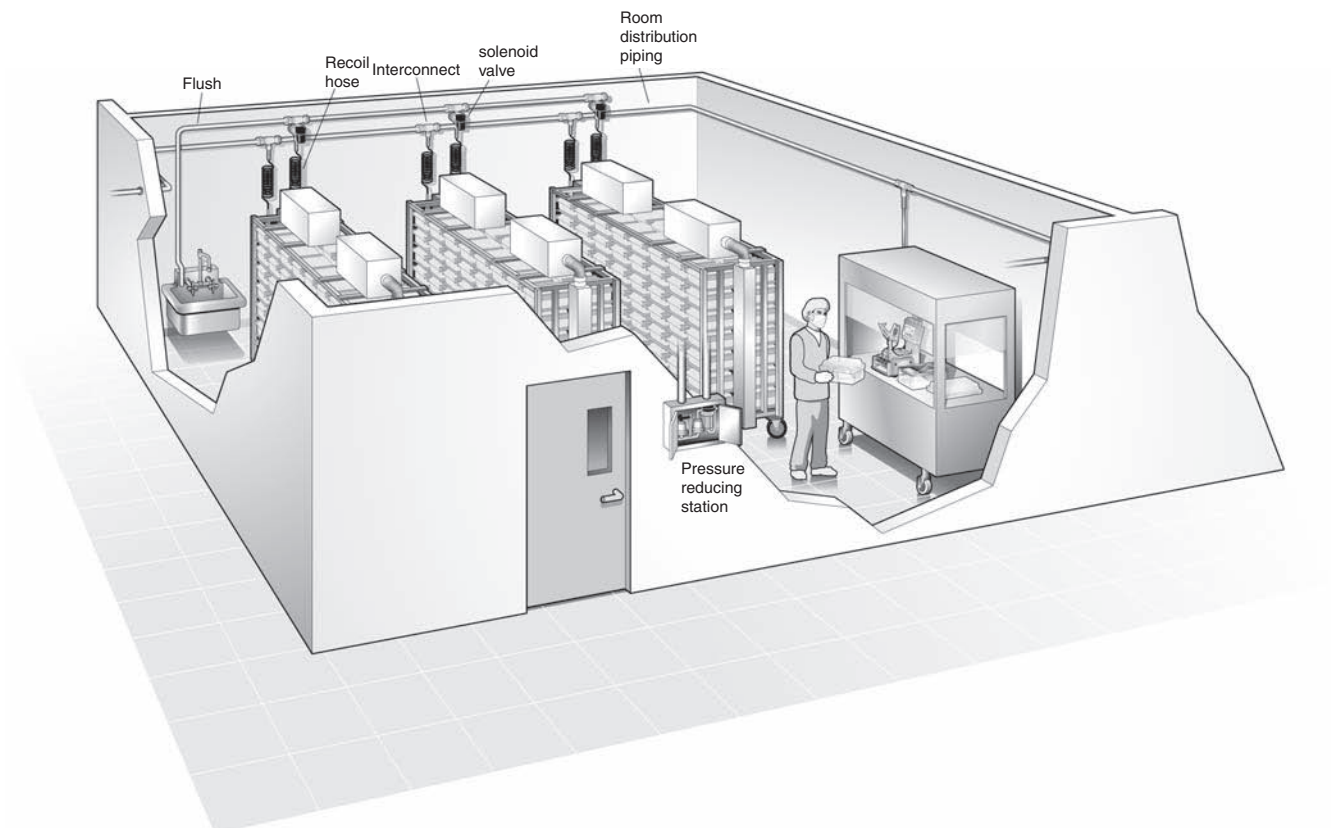

Fig. 32-2 Three-dimensional drawing of a mouse room with an automated watering system. Note the height of the room distribution piping to protect it from damage by moveable racks.
Courtesy of Edstrom Industries, Inc.

Following attachment, formation of a mature biofilm can be completed, depending upon circumstances, within hours to weeks (Mittelman, 1985). As the biofilm grows, fragments can detach, flow onward to downstream water valves, and be consumed by the animals. Consumption of agents such as *P. aeruginosa* can have untoward consequences for rodents that are immunosuppressed, and for certain experiments (Lindsey *et al*., 1991). The unfortunate reality is that these micro-organisms can adhere to all known plumbing materials (Mayette, 1992).

Although some biofilm formation is inevitable, the extent of development can be minimized with effective AWS. Installation of microfiltration systems, such as filter banks (Figure 32-5), prior to the treatment and distribution aspects of the systems can entrap the bacteria normally present in municipal water and reduce the development of biofilm. Eliminating large fissures in the piping circuit, such as O-ring joints, will prevent deep biofilm pockets which are harder to sanitize and are more corrosive. Also, installing pipes with electropolished lumens will aid in corrosion-resistance. The continuous water flow and/or periodic flushing component of AWS operation will also suppress biofilm formation. Where intraluminal sanitation is performed with chlorine, ozone or other appropriate sanitizers, lower-profile biofilms present shorter diffusion distances for the agents to fully penetrate and destroy or impair the organisms. Sanitizing at high frequency (e.g., daily) prevents biofilm recovery and aids in suppression. Although there are no independent studies of water quality comparing flushing to recirculation, manufacturer studies (Edstrom Industries, Inc., Waterford, WI) have shown that flushing offers more consistent, higher-quality drinking water as measured by bacterial counts.

The disadvantages of AWS are high installation and associated maintenance costs, the requirement for naive animals to learn to use the system (and their susceptibility to fail at it), and the increased risk of malfunction leading to flooding, dehydration and mortality (Huerkamp *et al*., 1994; Hobbs *et al*., 1997). Examples of possible failures related to AWS include high-pressure drifts in the water supply rendering the valves too difficult to manipulate, flooding from bedding particles inserted by mice into the valve, and air pockets in the manifold system obstructing water flow. Unlike bottles, which contain a finite water volume, flooding is much more severe with AWS because, in theory, all of the water in the local

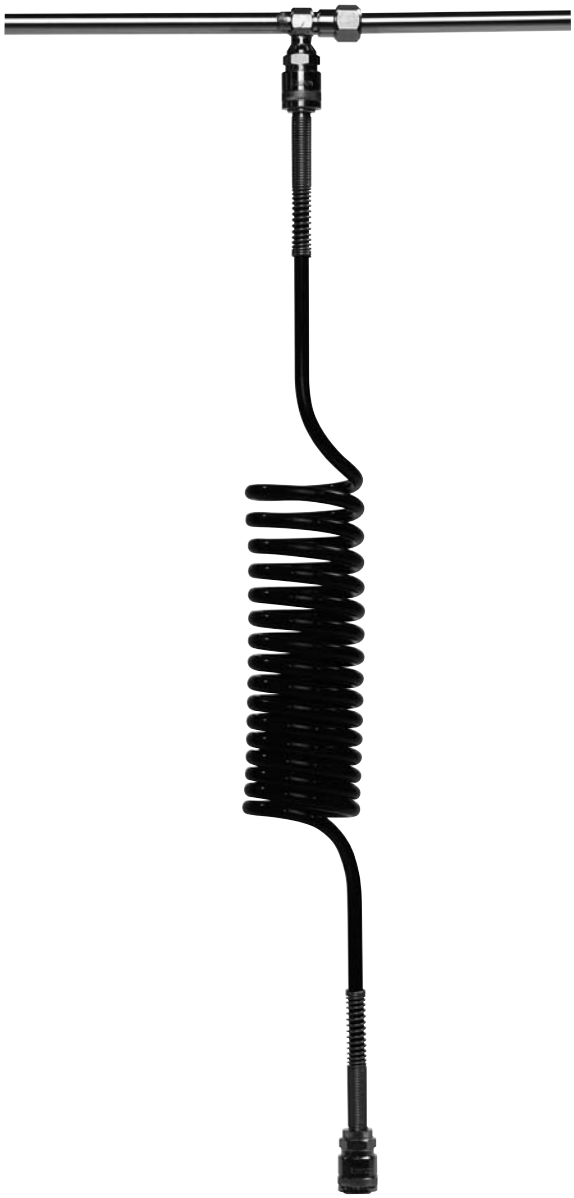

Fig. 32-3 A recoil hose made of PVDF.
Courtesy of Edstrom Industries, Inc.

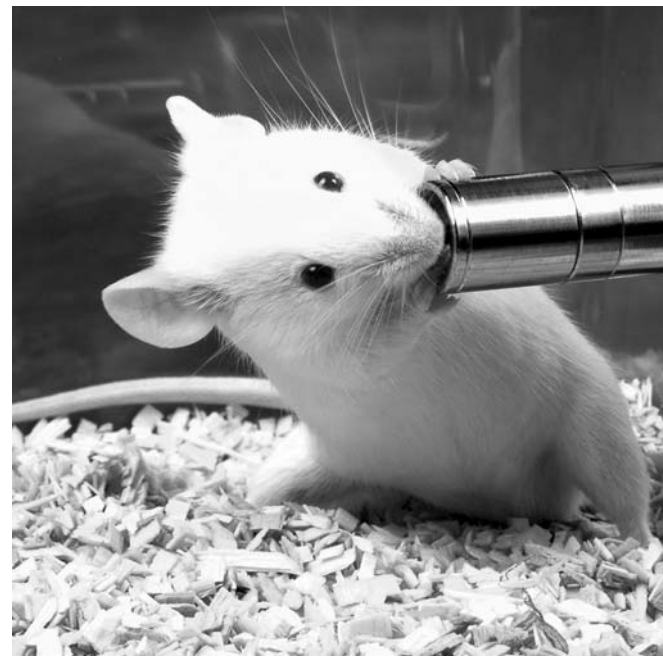

Fig. 32-4 A mouse activating the specialized drinking valve; the mouse deflects the valve stem with its mouth, enabling drinking water to pass around the O-ring and diaphragm that provide the seal.
Courtesy of Edstrom Industries, Inc.

Fig. 32-5 Filter bank station. This newer filtration system steps the drinking water through a series of filters (5 micron→1 micron→0.2 micron) to enable removal of particulates, protozoa, and bacteria from the drinking water.
Courtesy of Edstrom Industries, Inc.

reservoirs could flow through a leaking valve into a cage and cascade onto other cages below. Fortunately, vendors continue to improve the technology and reliability of the valves and systems. A future enhancement may lie in the application of nanotechnology to enable individual valve flow to be monitored and alarmed. AWS may also promote the transmission of pathogens that are present on watering valves, particularly where they are integral to the rack (Lipman *et al*., 1993; Macy *et al*., 2002). For example, cages removed from one site and returned to a different vacated spot are also moved from one stationary watering valve to another, and thus the mice may possibly encounter new micro-organisms in the process.

3. *Packaged Water Systems*

Because of the limitations of bottles and AWS, packaged water systems have emerged as a third alternative. These offer increased automation of the water-filling process to varying degrees, and correspondingly reduce human handling. In essence, sterile film pouches with a silicon film port are

filled with water, and a disposable or multi-use water valve is inserted at point-of-use. The bag and valve are then placed in a holder in the cage, similar to a water bottle (Figure 32-6). For older cage types, such as those with wire-bar lids, special holders or lid liners are available to enable conversion for packaged water use. These systems are suitable for all forms of water, including medicated preparations, and also have decreased container weight as compared to bottles. Like water bottles, packaged systems also eliminate the risk of catastrophic flood that can be associated with AWS. Biofilms are presumably prevented and water quality preserved, as the valves prevent water backflow and the bags are changed and discarded regularly. Equipment needed for these systems is generally less expensive to acquire and install than AWS.

At this time, there are two product options on the market. Hydropac™ (Lab Products, Seaford, DE) is an automated, high throughput filling system permanently installed in the clean cage-wash area or other appropriate site, and capable of filling 1,800 pouches per hour. Batches in crates can not only be distributed through a single facility; one filling station can also be used as a core resource to supply water to be hauled to other decentralized sites. By the same token, a repository of filled bags can serve to meet needs for emergency water. The manufacturer claims that operating costs are 75 percent less than a bottle-based system (LabProducts, 2007). Both the bag and valve in this system are disposable, which potentially improves hygiene, but also increases waste. The Sipper Sack™ system (Edstrom Industries, Waterford, WI) is designed for in-room use. The filling device attaches to the AWS manifold, and bags are filled on demand by manually attaching them one-by-one to the filling device during cage change. Purchase cost and versatility are obvious advantages. Both systems have available companion disposal carts for collecting waste bags and water for dumping. Overall evaluation remains incomplete, as these novel systems do not have the benefit (or curse) of a history of use such as is associated with water bottles and AWS.

Another drinking water alternative that actually predates the packaged liquid water systems is water gel packs (van Bekkum *et al.*, 1983), such as the commercially available Napa-Nectar™ (SE Lab Group, Napa, CA) (Figure 32-7). These have traditionally been used to enable long-distance shipments of crated rodents. Gel packs may be used in lieu of bottles when accommodating weanlings or naive adult rodents to AWS. Because of a long shelf-life and compact packaging, a repository of gel packs can provide emergency watering during times of supply interruption. A 4- to 8-oz pack may sustain five adult mice for up to 7 days. In other cases, the packs may be suitable for special application in metabolism studies, rodent quarantine or biohazard areas.

B. Plumbing Considerations for Automated Watering Systems

1. *Introduction*

Automated watering systems must be designed to efficiently deliver water that is clean and free of contaminants. As such, these systems must be designed so that the microbial populations are controlled and/or reduced. Daily flushing of the system, in addition to water treatment and purification, is critical for sustaining high-quality drinking water. Important elements

Fig. 32-6 A Hydropac™ being placed within the wire-bar lid, in the location normally used for water bottles.
Courtesy of LabProducts, Inc. (http://www.labproductsinc.com).

Fig. 32-7 Hamster consuming gelatinized water (NapaNectar™) inside a transport container.
Courtesy of SE Lab Group, Inc. (http://www.selabgroup.com).

to consider when designing a system include understanding the quality of the incoming water supply, choosing appropriate water purification processes and residual disinfectants, and selecting the proper materials for construction.

The design of an animal drinking water distribution system is very important to water quality. Systems must not have sections of pipe with low or infrequent flow (so-called "dead legs"); such sections enable water to collect and stagnate, leading to bacterial overgrowth and system contamination. Dead legs are produced when a length of pipe terminates without an outlet, or anywhere water turnover is not assured by flushing. Dead legs provide a location for waterborne bacteria to thrive and multiply and, by their nature as low-flow sites, also protect bacteria from sanitization.

2. *Distribution System Design*

a. Water Treatment

Before drinking water reaches the laboratory animal, it travels a course of piping and passes through treatment and/or purification processes. Water coming from a well or municipality flows through the municipal infrastructure to the building containing the animal facility. From that point, it is segregated into uses for potable water, laboratory water, etc. For animal drinking water, additional purification is usually required, and may range from particle filtration to more complicated treatment such as reverse osmosis filtration.

It should always be assumed that a facility's incoming water supply has some level of contamination in the way of particles, dissolved ions, organic compounds, bacteria and other microorganisms. This is not to imply that the water is unsuitable for human consumption; municipal water has been treated to comply with standards and regulations for safe drinking water. However, potable water is not sterile, nor is it free from metals or other compounds; basically, public drinking water contains contaminants that may introduce variables to research. Incoming water quality will change with the seasons. Rainy seasons induce more runoff, which introduces more animal waste and pesticides. Dry seasons increase the concentration of contaminants. Municipalities have water treatment processes for potable water, but because of the sensitivity of modern animal models and strict requirements of the medical research being conducted, they should not be relied upon for animal drinking water.

Following purification and treatment, water is collected in a storage tank. The size and quantity of storage tanks is determined by projecting the usage for drinking and flushing, as well as making provisions for a disaster plan. As a starting point, a formula which considers the number and type of animals, the number of cage racks, the number of flushes per day, any ancillary equipment (bottle fillers, etc.), and the number of days of desired storage is used to help make this projection. Adjustments are made based on any additional customer requirements, available tank sizes and floor space to determine the actual tank size used.

b. Distribution Piping

Water is pumped out of the storage tank into a repressurization tank to maintain a pressure of 40–55 psi (2.758–3.792 bar or 275.790–379.211 kPa). This pressure is required to push the water through the system. Water consumption by the animals is low relative to the volume of water in the distribution system; therefore, the repressurization tank is utilized so the pumps do not have to run continuously. Water typically enters 3/4-inch external diameter 316 L stainless-steel distribution pipes for delivery of water into the animal facility. It travels to the pressure-reducing stations to reduce water pressure to an appropriate level for animal consumption. Drinking valves for mice operate on a range of 3–5 psi (0.207–0.345 bar or 20.684–34.474 kPa), while valves for dogs and pigs operate at 15 psi (1.034 bar or 103.421 kPa).

c. Pressure-Reducing Stations

The pressure-reducing station (PRS) consists of low- and high-pressure regulators, solenoid valves, sensors to monitor pressure and flow conditions, and possibly a particulate filter (if not installed upstream of the PRS). The purpose of the two different regulators is to provide lower pressure for animal consumption (3–5 psi) and higher pressure for flushing (15 psi). Sensors tie back to a controller that initiates the flushing schedule and monitors the system for problems. Each station can serve up to 25 cage racks. The pressure-reducing stations should be designed with monitoring devices to detect unacceptable pressure or flow deviations and alarm appropriately.

d. Room Distribution Systems and Recoil Hoses

Water flows out of the pressure-reducing station into the animal rooms via 1/2-inch external diameter stainless-steel piping. Room distribution system (RDS) piping is typically wall mounted at 6–8 feet above the floor to keep it above the mobile racks. At each rack position there is an interconnect tee fitting, which is a quick-disconnect coupling that attaches to a flexible recoil hose made of polyvinylidene difluoride (PVDF) and stainless-steel components (Figure 32-3). The recoil hose extends from the distribution piping to the interconnect fitting on the rack manifold piping. It is called a recoil hose because it re-coils itself when disconnected from the rack; this causes the hose to lift up and out of the way.

e. Rack Manifolds

The manifold is the piping that is mounted on the cage rack. It is typically made of type 316 stainless steel, and has

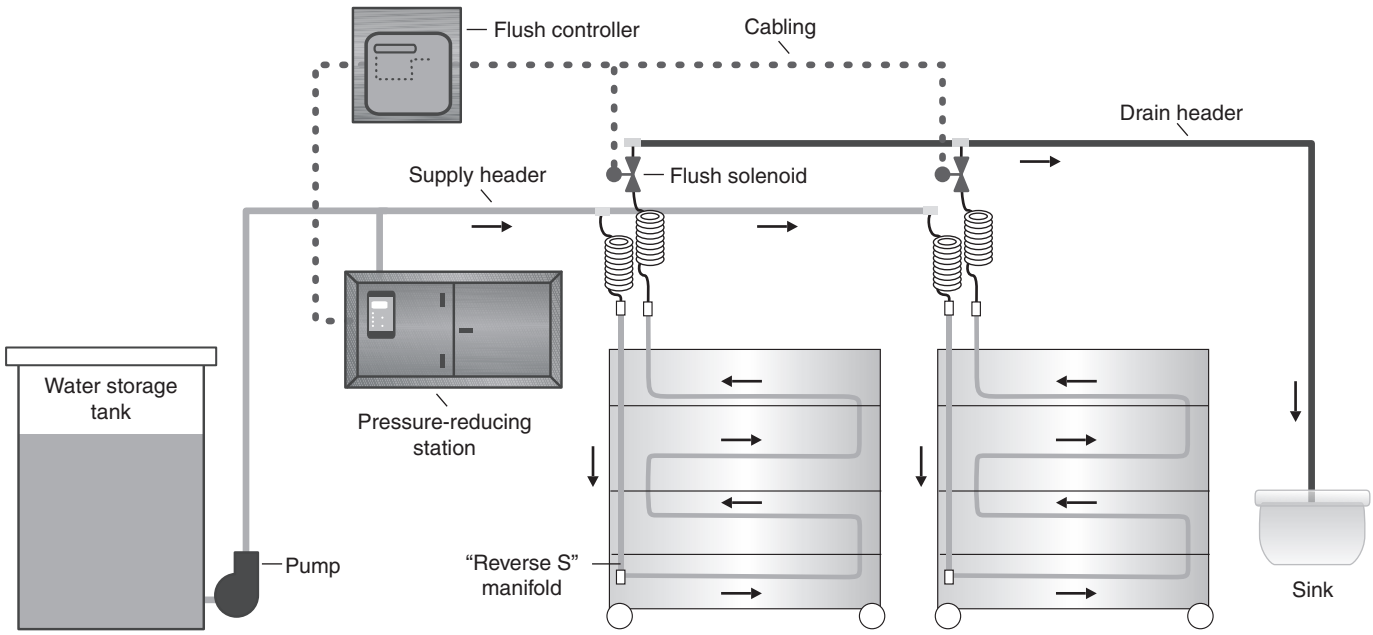

Fig. 32-8 A schematic drawing of a non-recirculating system that features the capability to flush the rack manifolds. This figure also demonstrates the "reverse S" design feature for rack manifolds.
Courtesy of Edstrom Industries, Inc.

an attachment for a drinking valve at each cage position. Water enters the manifold at a connection point near the top of the rack and is carried first to the bottom row of cages, then follows the piping through each course of cages back toward the top of the rack. This configuration is called "reverse S," and assures that all air is bled from the manifold piping (Figure 32-8). This is very important, because entrapped air could form bubbles at a drinking valve outlet, preventing animals from receiving water. By filling from the bottom shelf first, and by having a single, continuous path flowing upwards, all air can be readily vented from the manifold. In addition, the reverse S design does not contain any dead legs, which makes sanitization and disinfection protocols more effective. This configuration is typically used on caging for rodents, rabbits and non-human primates.

Manifolds for dogs and livestock are different, since these species are typically housed in larger, free-standing kennels or runs. A stick manifold is the simplest dog manifold. It is a length of pipe that is bolted to the wall or clamped onto the kennel fencing. The drinking valve is attached at the bottom of the manifold. An adjustable manifold is similar to the stick manifold, but is mounted in a channel bracket, allowing the height to be adjusted for different-sized dogs or growing dogs (Figure 32-9). Older designs had a distinct disadvantage in that they were essentially "dead legs," enabling drinking water to stagnate. More recently, flow-through designs provide system flushing benefits for dogs and other large animals.

f. Drinking Valves

Water is accessed by the animals through a drinking valve. Animals operate the valve by biting or licking the drinking-valve stem. There are drinking valves for every species and application, each designed for the way the animals tend to drink, whether gnawing, biting, licking or nosing.

Various types include a standard tip for species or strains that tend to play with the valve, or that drink by licking or nosing. Typically, rats, mice and guinea pigs use standard-tip valves. Biased-tip valves have a slant cut out of the top of the tip, making them more suitable for gnawing animals such as rabbits and certain primates. Shielded-tip valves are designed for mice and rats in ventilated cages. These valves are specially designed to prevent bedding from entering the valve and holding it open (Figure 32-10).

Flow rates vary depending on the species. For example, a rodent valve is designed to dispense 25 ± 5ml/min, whereas a rabbit valve dispenses 40 ± 5ml/min.

g. Distribution System Materials

The composition and construction of an animal drinking water system directly impacts its longevity and reliability, and the quality of drinking water that it yields. State-of-the-art automated watering systems incorporate stainless steel into their design of drinking valves, manifolds, room distribution piping and pressure-reducing stations. For optimum system life and

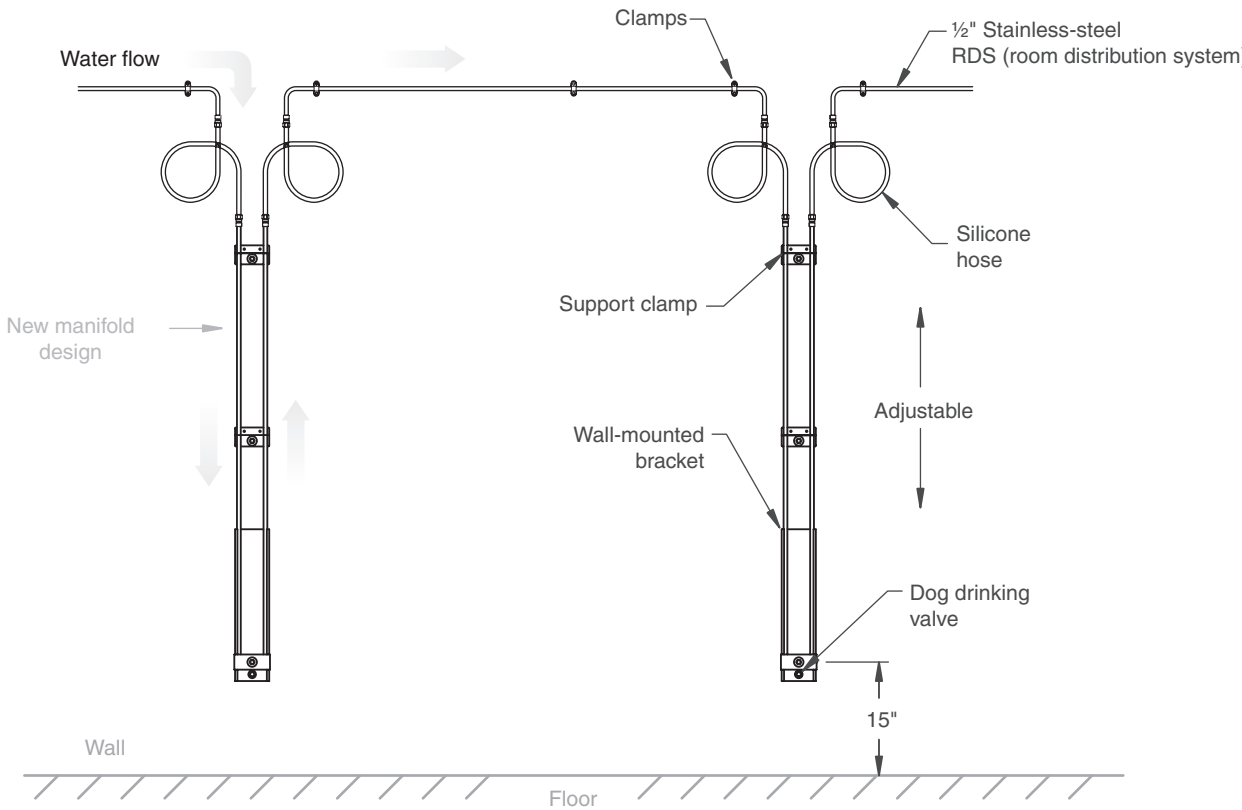

Fig. 32-9 Manifold for an automated watering system for dogs and/or livestock. Note the adjustable nature of the manifold to enable varying heights for the drinking valve based on the species housed.
Courtesy of Edstrom Industries, Inc.

Fig. 32-10 A rodent drinking valve that is shielded to prevent bedding from entering the valve, and guarded to prevent the valve stem from being accidentally deflected.
Courtesy of Edstrom Industries, Inc.

effectiveness, 316L stainless steel, silicone and PVDF are the materials of choice, and should be used whenever possible.

1. *PVC/CPVC.* This material is inexpensive and fairly simple to install. However, it makes for a dirty installation in that it uses plastic fittings that create cracks and crevices, and glued joints which expose glue to the drinking water system.
2. *Stainless steel*. Stainless steel is available in various grades, the most common for the research setting being 304 and 316. For animal drinking water type 316 is recommended, because it offers a higher resistance to acidification and chlorination. The higher chromium and nickel content in type 316 stainless steel creates a passive oxide film on the surface which protects it from chemical attack. In addition, stainless steel can be electropolished and passivated to provide even greater corrosion resistance and esthetic qualities. Systems utilizing lower-grade stainless steel may use glued joints, but on higher-grade systems, compression fittings with internal silicone seals are used to eliminate internal cracks and crevices. Stainless steel is also autoclavable.
3. *Silicone*. O-rings and seals within the system are made of silicone. Silicone is inert to all disinfectants in the water, and is also autoclavable.
4. *Polyvinylidene difluoride (PVDF)*. This form of plastic is used for recoil hoses. PVDF can withstand chlorination (0.5–50 ppm), acidification (pH 2.5) and autoclaving. Its

flexibility and durability enable it to last many years in the animal facility environment.

5. *Other materials*. Other materials commonly used in household plumbing, such as copper, brass, carbon steel and galvanized piping, should be avoided in the laboratory setting. Copper and brass are not compatible with RO water and, if used, will slowly leach metallic ions into the water. This will not only eventually lead to leaks, but also increase the contamination in the water. Carbon steel will rust, and galvanized coatings are easily damaged, allowing corrosion to develop. Additionally, these materials are not compatible with disinfectants like chlorine and acid, which are commonly found in the research environment. These sanitizing chemicals will damage these piping materials, causing premature equipment failure.

3. *Distribution System Options*

a. Introduction

The type of watering system a facility chooses will be based upon the requirements of the research being conducted, as well as the goals of the facility. Recirculation systems strive to conserve water by reusing it, whereas flushing systems constantly bring in fresh water. Recirculation does reduce water usage by the facility, but water quality could be affected as a result. Both systems require that line installation be such that there are no "dead legs" or other places where water can stagnate (Edstrom, 2003).

b. Non-Recirculating (Flushing) System

Flushing systems regularly bring fresh water with residual disinfectant into the room distribution systems, and possibly even the rack manifolds. When the system has flushing capability, an electric solenoid valve is present at the drain line (Figure 32-11). This valve is opened automatically, typically on a daily basis, by an electronic controller. The controller also elevates the system pressure temporarily approximately three- to five-fold (in the vicinity of 15 psi), and the manifold is vigorously pulsed with a volume of water with or without a sanitizing agent. The water exiting the manifolds flushes through the runoff lines to a nearby sink or drain. The solenoid then closes and the pressure is restored to the normal 3- to 5-psi range. These automated systems require coordination between the plumbing and electrical installation contractors, especially when the low voltage lines that operate the solenoids are required to be within the conduit (author's personal experience). Flushing can be performed on both the room distribution piping and the rack manifolds.

1. *Room distribution system flush*. In this type of system, water is flushed through the header and the RDS, but not through the rack manifolds. These are simple single-pipe systems, but because the water in the rack is never turned over, it is common to have very high bacterial levels within the rack manifold.

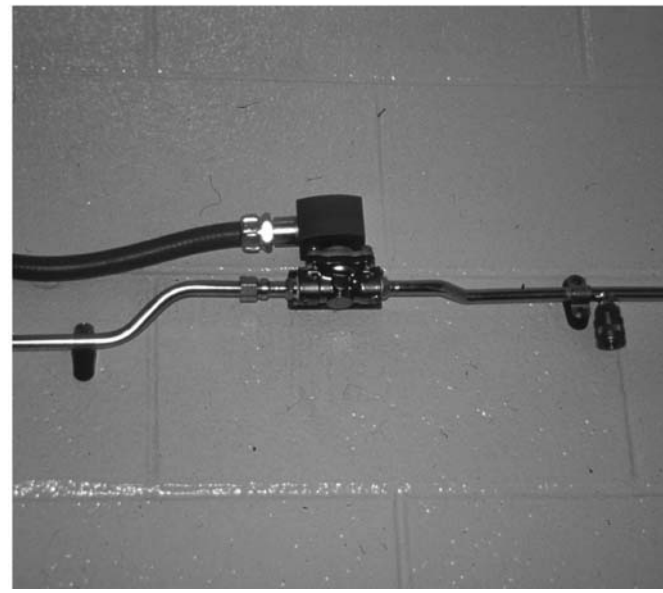

Fig. 32-11 Solenoid valve on a non-recirculating system. Electronic activation of this valve enables higher-pressure water to flush through the system to reduce biofilm development.
Courtesy of the University of Michigan.

2. *Rack flush*. Because animals consume relatively small volumes of water on a daily basis (approximately 5 ml per mouse per day), the water turnover in the distribution system is very low. A typical manifold on a mouse rack holds 3,870 ml of water. Even if 700 mice were drinking from one manifold, all of that water would not be consumed in a day's time. This is the justification for daily rack flushing. Rack flushing can be done manually by opening a drain on the rack, or automatically with a solenoid valve. In an automated rack flushing system, there is an additional connection at the top of the manifold for a recoil hose to attach to a flush line (Figure 32-8). By using electric solenoid valves, computer controlled electronic timers perform the flushing. Automated rack flush systems do require a second set of piping for connection to the drain side of the racks, and thus are more expensive to install than room flushing systems. An alternative is to dispense with the electronics and design for flushing, and have personnel manually open the drain valve at the end of each rack manifold. This is discouraged, however, as the manual flushing process is reliant upon training and consistent commitment, and may be forgotten should staff become distracted, or be done inconsistently or incompletely by inadequately trained personnel.

c. Recirculating System

A recirculating system saves water by recycling it through the system, instead of flushing it to a drain. The differences between a recirculating system and a flushing system start

after the water leaves the storage tank. Instead of water entering a repressurization tank, pumps continuously circulate the water through the distribution system. Water is carried to the animal facility through 3/4-inch external tubing after passing through an ultraviolet (UV) light, which provides a point source disinfection of the water. Recirculating water system pump motors should be equipped with a current probe and alarming capability in the case of failed electrical supply. The two main design schemes for recirculating systems are room distribution system recirculation, and through-the-rack recirculation. These systems conserve water and do not require solenoid valves, electronics or flush sequencing controls, but also do not offer the prospect of daily, automated in-line sanitation flushes. The constant flow of water by design makes the leak detection by electronic means more difficult than intermittent flushing systems (Edstrom, 2003).

1. *Room distribution system recirculation*. In this type of system, water is recirculated through the header and the RDS, but not through the rack manifolds. Water is pumped from the storage tank, through the UV unit, and through the supply header at high pressure. Each room distribution loop then feeds off of the supply header at a controlled, reduced pressure. Water exits the RDS loop and goes back to the storage tank through the return header. These are simple systems to develop and install, but because the water in the rack is never turned over it is common to have very high bacterial levels within the rack manifold.
2. *Through-the-rack recirculation*. In a rack recirculation system the water is recirculated similarly to the room distribution system, except that the water also enters the rack manifolds, bringing fresh water to each animal drinking valve. This is particularly important for species, such as mice, which consume small amounts of water. In this system, the water exits from the drain point of the rack manifold and then goes back to the storage tank through the return header. This type of system utilizes the same manifolds, quick disconnects and recoil hoses that are used in a flushing system. Through-the-rack recirculation provides distinct engineering challenges. It is difficult to balance the flows to ensure that every rack is receiving the minimum gallon/hour flow requirements. For instance, removing one rack from the system changes the flow for all the other racks. This scenario is similar to the challenges experienced with balancing airflow through animal rooms.

C. Adjunct Equipment

1. *Bottle Fillers*

Bottle filling devices afford varying degrees of automation of the potentially laborious task of dispensing tap, purified and/or treated water into bottles for animal consumption. The equipment options range from hand-held, manually-controlled systems able simultaneously to fill cases of 12–24 bottles per batch to fully mechanized processes capable of automatically filling and capping (and uncapping and dumping) hundreds of bottles per hour (Kronos™, IWT, Casale Litta (Va), Italy). Bottle filling stations (BFSs) are ordinarily designed and installed with a reservoir tank in combination with a booster pump, a low volume alarm and a proportioner. The latter is used to inject chlorine, acid or water-soluble medication into the water for administration at point-of-use. Proportioners and bottle fillers may be combined as one unit or can be separate, depending upon the manufacturer, line of products from a specific manufacturer, or application in the facility. The reservoir tank is connected to the designated water source and the level within the tank is controlled independently, ensuring an adequate and uninterrupted supply for the station. The tank may be situated immediately adjacent to the BFS or at a distance, usually 10 feet or less, away.

The benefits of BFS and proportioners over purely manual water filling or treatment are lower operating costs, uniform filling of bottles, water waste reduction and consistent water treatment. In some cases, integration of the bottle filler/water proportioner with a monitoring system allows the output of filled cases to be recorded and documents any changes in program settings, pH sensor readings and any system abnormalities (Watchdog V5®, Edstrom Industries, Inc., Waterford, WI).

The most scaled-down bottle filling application, other than filling bottles one-by-one by hand at a faucet or with a hose, is to use a hand-held, stainless-steel or PVC manifold with the configuration and number of nozzles corresponding to the water bottle case in use, to fill bottles at a sink or suitable platform. The manifold is connected to a water source (e.g., faucet) via a hose and controlled manually or by foot-pedal. Fill manifolds should be interchangeable to allow for the efficient management of multiple size bottle cases. This application is suitable only for small-scale operations or where space is tight and labor is cheap and plentiful.

The next step up is a traditional manual BFS, nominally consisting of a floor- or wall-mounted frame and housing, full backsplash, fill manifold with nozzles, and case retainer, all constructed of high-grade, corrosion-proof type 316 stainless steel. A case of clean, empty bottles is placed on the rails of the fill table and then aligned with the fill nozzles once pushed forward against the stop of the case retainer. A manually operated ball valve is used by an attendant to start and stop water flow, and the water is dispensed through the filling manifold into the bottles. The fill table basin is connected to a drain to catch any spilled water. These systems should ideally be designed for upgrade to allow for water treatment and programmability, and are most suited to facilities where large numbers of bottles are handled and filled daily.

Programmable BFSs are similar in design to the traditional manual alternative, but feature automatic fill-cycle control

activated by either a timer-controlled push-button or an electric eye. Systems should offer the versatility of user-programmable fill times for multiple bottle capacities, and pH monitoring with display should be provided for acidification situations. After the bottle case is inserted and the BFS is activated, the fill cycle starts and water is pumped from the reservoir tank at a constant rate. If a water treatment option is selected, the injection pump injects the chemical additive into the water stream at a preset flow rate to provide the desired mixture level. The flow of water is automatically stopped when the programmed fill time expires, and the case can be removed. The process is repeated for each case of bottles. Units should be self-purging to prevent residues and promote nozzle cleanliness by regular flushing if idle for more than a few minutes, or where a switch is made between treated and untreated water. Some units offer the versatility of removable side-walls, allowing the loading of cases from an integrated conveyor feed system. Programmable BFSs are recommended in cases where water bottles are used almost exclusively (no automated watering systems) and processed through the cage-wash room daily.

Where water bottle throughput is high, automation takes on a greater premium. Conveyorized systems that fully handle water bottles, including uncapping, dumping, washing, filling and recapping, are commercially available for installation in cage processing resources and allow human resources to be allocated to more critical duties. The most prominent among these systems are Kronos™ (IWT, Casale Litta (Va), Italy) and AutoCap (patent pending) (Allentown Caging Equipment Company, Allentown, NJ, USA). Lastly, for throughput capable of handling thousands of rodent caging implements per day, programmable BFSs can be served by articulated industrial robots within the context of a fully automated and integrated cage, bottle and bedding processing system (Detach System, Detach AB, Strangnas, Sweden).

Optimally in all cases, the fill manifold and case retainer of a BFS should be custom designed to hold the user's bottle case size of preference, and should allow for quick change-out to accommodate more than one size case. The nozzles on the manifold should be removable, replaceable and cleanable. Manifold or filler header heights should be easily adjustable to allow for different bottle heights. Where manual labor is used to handle bottle cases at the BFS, the fill-table height should be compatible or adjustable to the user's water bottle carts and staff anthropometrics. Reservoir tanks with cone bottoms are preferred, as they allow for easy cleaning.

2. *Proportioners*

Proportioning devices enable the accurate mixing of a base treating solution into animal drinking water at a user-determined level and it to be dispensed through a BFS or the piping of an automated watering system for the purpose of chlorination, acidification or medication. Proportioners may be obtained and installed in conjunction with water distribution equipment or separately. They consist of a control panel cabinet and both a reservoir tank and pump and a solution tank of chemical additive with a separate injection pump. If used in conjunction with a BFS, the reservoir tank is shared between the two devices. As for BFSs, the former assembly ensures a constant flow of water, but in the case of a proportioner is integrated with the solution tank and injection pump to enable blending of chemical additive into the water. This ensures fresh and uniform treatment.

When used in combination with a BFS and activated, the booster pump draws water from the reservoir through the proportioner at a constant rate and, if selected, the injection pump automatically injects the chemical additive into the water stream at a preset flow rate providing the desired mixture level. The flow of water is automatically stopped when the programmed fill time expires. The control panel allows for the user to select the dispensation of plain or treated water, adjust the time of fill, and start and stop the process. Displays on the control panel should allow for chemical additive tracking, pH monitoring (where applicable), and alarms for low tank volume alarms or unacceptable pH/chemical extremes.

Both tanks typically have about a 30- to 40-gallon capacity. Similar to bottle filling devices, proportioners stand less than 6 feet high and, including the solution tank, consume a footprint of approximately 7 square feet. If used as a component of an automated watering system, a post-treatment storage tank is necessary and a dedicated treated water header must be installed between the water outlet from the proportioner and either the pressure-reducing station or recirculation loop. Where the system is designed for periodic flushing, the post-treatment storage tank must be pressurized.

Most BFSs, exclusive of proportioners and reservoir tanks, stand less than 6 feet high and require 7–8 square feet of floor space. In terms of design specifications, both the BFS and any proportioners must be connected to a 115 VAC power supply, the reservoir tank(s) must be coupled to the customer's 40- to 75-psi water source, and the drain on the BFS fill table must be plumbed to a drain line. A shut-off valve should be installed on the supply water line, and the line also should be designed to allow for the incorporation of charcoal or other filters. All plumbing on or connected to the BFS must be PVC, polyethylene or stainless steel, and compatible with potable house water, highly reactive pure water or low-pH extremes. Piping conduits and manifolds should allow for water flow of at least 5 gallons per minute and pressure of up to 75 psi.

3. *Water Softeners*

Scale on caging and other metal equipment items, including mineral deposits on valves used in automated watering systems, originates from minerals found in so-called "hard" water. Water hardness is caused by the presence of calcium and magnesium bicarbonate, iron and other minerals or metals (expressed in ppm or mg/l). By definition, water is generally deemed to be

"hard" if the mineral concentration exceeds 60 mg/l. In addition to causing scale deposits (particularly in situations where hot water is used, such as cage-washing and autoclaving), hard water also reduces the effectiveness of detergents, resulting in increased soap use.

According to the *US Geologic Survey*, 85 percent of domestic water is towards the "hard" end of the spectrum (Briggs and Ficke, 1977). Consequently, most animal research facilities will be faced with attenuating some degree of water hardness and demineralization of water for cage-washers, autoclaves and animal consumption. In general, the hardest water (greater than 1,000 mg/l) is in streams and associated groundwater in Kansas, Texas, New Mexico, Arizona and southern California (Briggs and Ficke, 1977). Moderately hard water (61–121 mg/l) is common in many of the rivers of Tennessee, in the Great Lakes, the Pacific Northwest and Alaska regions. The softest water occurs in New England, the south Atlantic and Gulf states and Hawaii. Unfortunately, geography does not afford a simple predictive value for water hardness. Hard and very hard water (>121 mg/l) can be found in some streams within most of the areas throughout the country, including interspersed in those locales where soft water is generally found.

Water softeners will remove essentially all calcium and magnesium, but only extract approximately 5–10 mg/l of iron. Fortunately, iron is generally not present at concentrations greater than 10 mg/l in domestic water. These metallic ions in the water are exchanged for sodium ions within the water softener. Because sodium does not precipitate out in pipes or reduce the effective properties of detergents, the detrimental effects of hard water are eliminated through softening. In those rare cases where the dissolved iron content in water is higher than 4 mg/l after water softening, an additional means of iron removal must be used. Technologies that might have application include aeration, additional specific catalytic filtration, manganese green sand filtration, ozonation and, possibly, chlorination.

Except for preventing scale accumulation on drinking water valves and reducing the risk of valve failure, softened water alone does not provide much additional advantage in terms of ensuring animal health or preventing confounding experimental variability. While the process removes calcium, magnesium and most iron which cause scaling in water lines, hot water tanks and water valves, it leaves residual chloride, organics and suspended sediment. Accordingly, for the most effective drinking water treatment, water softeners should be used in series after sediment and carbon filters and as pretreatment for any RO system. Softening the water prior to treatment by the RO system also extends the lifespan of the RO membrane and greatly improves the performance and economy of the RO system.

The process of softening is accomplished through a chemical cycle of exchange and regeneration. Filtered water is flushed over a resin bed which binds calcium, magnesium and iron and exchanges them for sodium ions. Eventually, the chemical matrix fully loads with calcium and magnesium and depletes the sodium, and the system is no longer capable of softening the water. To restore the ion exchange capability of the resin, the system regenerates by backwashing the resin to remove deposits, recharging the resin by immersion in a salt solution (brining) and then rinsing away excess salt and hard water ions to a drain. The strong brine, constituted by supplying the softener with salt, displaces all of the calcium and magnesium that has built up on the resin and restores sodium. Water-softening equipment uses three general methods of regeneration: timer, metered, and demand-initiated regeneration (DIR). The timer method automatically initiates and halts regeneration at preset intervals and regardless of use, as set by a time clock. Because it risks over- or under-regenerating the system, it is not recommended. Metered technology uses a digital electronic control valve controlled by an electronic meter. The application tracks the amount of water used, and once a preset volume has been softened it initiates the backwash cycle and regenerates. DIR operations track water treatment and hardness. Regeneration initiates only when the system has been used to capacity for optimum efficiency. DIR systems generally have two softening tanks and a brine tank, and while one tank is softening the other tank regenerates. Of these three methods, DIR is the most efficient. Both it and the metered method offer savings in salt and water usage over the time-clock method. The resin regeneration process time and frequency are governed by the size of the system and the initial condition of the water, but should generally occur every 5–10 days and requires several hours. The regeneration process, however, can be timed on most units so that it does not occur during "peak" hours. If there is no possibility of down time, a water-holding tank is necessary, or additional softeners.

Water softeners are sized and specified to the volume demand and the initial hardness of the water. Experts will need to be consulted to determine the specifications of water softeners required for a given facility, based on the needs for which the softened water will be used.

The ion exchange process of softening water can generate potential research and animal health risks unless additional effective purification (e.g., reverse osmosis, distillation) is performed. Since calcium and magnesium ions are replaced with sodium ions, the concentration of sodium in the water will increase. In areas where water is extremely hard, the amount of sodium introduced into the water may have subclinical effects on animals – for example, iatrogenic hypernatremia may confound experiments involving heart failure, chronic renal failure, coma, seizure, and situations requiring low-sodium diets.

4. *Monitoring Systems*

Water is critical for life, and the delivery of fresh, potable, uncontaminated water is essential for the maintenance of research animals. Because man-made systems are prone to failure, and often at times when facilities are not occupied and the trouble may not be readily observed or detected, it is

incumbent upon those responsible for operations to reasonably watch over and ensure reliable function. There is a broad range of parameters of importance related to plumbing and to be considered for monitoring. With respect to the water distribution system, these include the pressure within AWS water lines as well as water flow abnormalities, including leak detection. The UV light status, water pH and chemical concentration can be monitored for water treatment systems. Additionally, water proportioning devices and bottle filling stations can be monitored and alarmed to sense conditions of low reservoir tank volume, low solution tank volume, pH or chemical extremes, and to chart volume output. Likewise, reverse osmosis water treatment systems can be outfitted with malfunction alarms. Water system pump motors can be monitored at least to ensure the supply of electricity necessary for operation using current sensors and alarms.

Just as there is an array of potential water system complications, there exists a correspondingly diverse range of monitoring options. These can be divided into user-customized technological applications, water system specific monitoring programs, and comprehensive commercial products with the capacity to monitor myriad environmental conditions including those critical to water supply. Simple applications installed and specific to the user are most appropriate for small or unique uses. These most traditionally are represented by the classic in-line pressure gauge of encased dial and pointer design. Advancing a step, water flow sensors attached at specific points in the water stream can be connected to data loggers capable of minimally recording events (HOBO HO7 Event Data Logger, Onset Computer Corporation, Bourne, MA). Similarly, water system pump motors can be instrumented to at least ensure the supply of electricity necessary for operation using current sensors capable of recording relay contact events (HOBO HO7 Event Data Logger, Onset Computer Corporation, Bourne, MA). Alert-type functions, however, generally require network wiring and programming and/or software to activate a call list or alarming mechanism.

In large, complex operations, the most sensible approach is to use a service-supported, off-the-shelf application from a major service provider. Systems are at least water system specific, with potentially broader environmental applications, and developed and marketed by entities with a history of innovation and expertise in animal drinking water delivery; they include the Watchdog V5® (Edstrom Industries, Inc., Waterford, WI) and the Pin•Point Monitoring System (Systems Engineering Lab Group, Inc., Napa, CA). As an alternative, the monitoring of certain plumbing parameters can be added as a customized application to a general environmental monitoring system such as the Apogee® and InfoCenter Suite® Systems (Siemens Building Technologies, Inc., Siemens AG, Munich, FRG), Metasys® (Johnson Controls, Inc., Milwaukee, WI), or the Centron environmental monitoring system (Rees Scientific, Trenton, NJ).

As for the future, perhaps the most pervasive and difficult to manage and control situation within the animal research facility is the flooding of individual cages supplied with drinking water via AWS. Particularly problematic is that, unlike water bottles with a finite capacity, in theory unlimited volumes of water can pass through a malfunctioning valve into a cage and cascade onto lower-tier cages in a rack. In situations where animals are only visually checked for well-being once daily, the potential exists for relatively longstanding and devastating flooding conditions. Unfortunately, there is no affordable resolution yet in sight for early detection or the prevention of cage flooding in this circumstance. As rodent research becomes increasingly more complex and sophisticated, and expensive hybrid housing and phenotyping systems (Bohannon 2002) are developed to facilitate scientific inquiry, however, greater premiums will be placed on protecting the investment value of the research through animal life-monitoring, support and intervention engineering. If AWS vendors are to not only protect their existing market share but also gain an ever-increasing fraction of the water supply business, it will be critical to conceive and put into service technology capable of detecting, alarming and possibly terminating water flow deviations not only at the rack level, but also at the individual cage level. While this may not be practical under present circumstances, advances in nanotechnology may yield effective and eventually affordable approaches to the management of cage-level water flow aberrations.

IV. SPECIAL CONSIDERATIONS FOR AQUATIC SYSTEMS

The number of animal research facilities that include large populations of aquatic animals (amphibians and/or fish) has been increasing substantially, especially as the popularity of *Xenopus* spp. frogs and zebrafish as animal research models continues to grow. In some cases these facilities are self-sufficient and separated from the classical rodent-housing facility, and in other instances they are part of the larger vivarium complex. In either case, a few essential plumbing considerations must be met.

First, the type of water needed by the species, and the types available for the building, must be addressed in the planning stages. Details regarding the selection of water sources and the specifics of aquatic facility design can be found in Chapter 23 of this book. Browne *et al*. (2007) provide an excellent review of the needs for facilities housing aquatic amphibians, and Aneshansley (2005) and Bartlett (2005) provide information on rack-based aquatic systems and retrofitting standard animal facilities for aquatics, respectively. Simply stated, the water source and the necessary water condition for provision to the aquatic species must be pre-determined. This will then dictate the treatment processes necessary for conditioning the water, and the space and equipment necessary to accomplish the conditioning process.

Secondly, the daily volume of water that needs to be supplied, and drained, must be calculated. A common challenge in retrofitting older traditional animal facilities for aquatic species is the inadequacy of the water supply and/or the drainage capacity. For some facilities (such as those with vertical risers and below-grade drain pipes), changing the size of water supply pipes and/or drains can be much more challenging than for facilities that feature interstitial spaces. In addition, the sheer weight of full water-storage tanks, and the necessary flooring support, is an often overlooked aspect in renovating facilities for aquatic animals (Bartlett, 2005).

For facilities housing aquatic species, floor drains should have mesh coverings to prevent the escape of research animals as well as the introduction of vermin, and a regular disinfection program to help prevent disease transmission within the facility (Browne *et al*., 2007). Such a program may feature a holding tank which disinfects the drained water prior to discharge into the municipal wastewater system; this disinfection could be via heat and pressure, or through the addition of chlorine (Browne *et al*., 2007).

V. DESIGN CONSIDERATIONS TO MITIGATE DISASTERS

Persons familiar with disasters and disaster planning know that it is not a matter of *if* disasters will occur, but rather *when* they will happen. Disasters are cyclical events putting animal research facilities always in at least one of the four phases of a disaster: mitigation, preparedness, response or recovery (Heath, 1999, 2000). While disaster preparedness is a continual effort in which the phases of the cycle of emergency management are constantly being anticipated, reviewed and improved, effective preparedness optimally starts with disaster-resistant facility design (Comerio and Nathe, 1999; Vogelweid *et al*., 2003) and follows with regular and effective facility preventive maintenance. Facility design and construction should be of such quality that failures related to the installed plumbing system are unlikely and, when occurring, are contained and detected. A good program of plumbing and water supply system preventive maintenance, it follows, is enabled by design features that are easy to monitor, maintain and repair proactively (Heath, 2000; Vogelweid *et al*., 2003). Eliminating existing and common causes of everyday plumbing disruptions, such as leaky pipes or obstructed sewage lines, increases the threshold at which adverse events, such as periodic burst pipes or regularly backed-up drains, lead to major disruptions (Heath, 2000; Vogelweid *et al*., 2003). Design should also facilitate, and not impede, the subsequent steps of disaster planning of personal preparedness, work-site preparedness in the form of contingencies for continuity of water supply, and even community preparedness (Heath, 2000).

Disaster prevention through facility design seeks to reduce direct and indirect losses resulting from major disruptions by minimizing adverse impacts and containing losses. Direct losses include distress, injury and death of animals (or even humans); damage to buildings, equipment and property; loss and corruption of research data; and delays in the publication of scientific data (Heath, 2000). Indirect losses from disasters include a loss of institutional competitive edge in research, erosion of institutional reputation, and possibly even decreased local economy as regular trade with local vendors is reduced (Heath, 2000).

While adverse incidents and disasters related to plumbing can be the result of natural, technological, programmatic or civil causes, technological hazards are the most obvious, and involve events associated directly with the sources of water in the facility, filtration and treatment modalities, pumps, pipes and distribution systems, and sewers and drainage systems. As a rule, technological failures are difficult to predict or foresee, have no established patterns, are preceded by little or no warning, and have the potential to cause substantial loss of science, animal life or property value (Anderson, 1998). Risks of natural origin include weather, seismic or ocean-related events, and are caused by climate and geography, while programmatic hazards are failures of people, programs, training or compliance (Anderson, 1998). Civil hazards are deliberately harmful human acts, ranging from small isolated incidents to larger-scale destruction (Anderson, 1998), and might include damage/vandalism caused by animal rights terrorists or deliberate absenteeism, such as would occur during a labor strike. Although large-scale incidents attract widespread attention, emergency management agencies have long recognized that, regardless of the cause (and scale), most disaster origins converge to cause similar impacts at the facility level (Anderson, 1998; Heath, 2000). It must also be appreciated that while some disasters may be the consequence of a single event, others may be small, chronic and cumulative in effect. Lastly, while most initiating events may have predictable detrimental consequences, others may have ramifications that are difficult to forecast (Gerrity, 1990; Alderson and Garnett, 2002).

The general operative rule regarding disasters is that their ultimate impacts are predictable disruptions in the functions necessary to maintain an appropriate standard of animal care and research continuity (Heath, 2000). For example, many "natural disasters," such as tropical storms, earthquakes, blizzards and floods, all lead to common secondary effects (Anderson, 1998), such as power outages causing AWS pump failures, road closures resulting in insufficient staffing to service water bottles, and municipal water that may no longer be potable (but potentially the only option for maintaining animal life). The goal must be to prevent likely and common effects on function from any type of disaster, and to reduce the likely consequences resulting from these effects (Anderson, 1998; Heath, 2000). Emphasis on this approach to design is often more effective than designing to account for specific disasters. It focuses on the consequence of the lost function – such as loss of power, inadequate staffing or building flood – rather than the specific cause. Vivarium design

that focuses on being incident-resistant typically accounts for a limited number of scenarios, and therefore actually increases vulnerability to unexpected disasters (Heath, 2000).

Additionally, disasters related to plumbing and the water supply can be either momentous or ongoing and incremental. An example of the former is the catastrophic rainfall and flash-flooding in Houston, Texas, in 2001 from Tropical Storm Allison, which deluged research facilities and resulted in the loss of research animal life at several institutions (Schub, 2002). A technological example of a momentous disaster would be a ruptured water pipe within the confines of the facility, undetected for an extended period of time, resulting in extensive localized or general internal flooding. An illustration of an ongoing and/or incremental disaster is sporadic, uncontrollable flooding of mouse cages on AWS causing intermittent loss of mouse life and experimental disruption of such frequency that investigators lose confidence in the AWS system and cause it to be abandoned. Corollaries are those cases in sewage lines of inadequate diameter or of insufficient slope towards the main drain line existing in livestock housing areas. If these situations require manual coarse waste removal prior to hosing of the pens by animal-care technicians, there will be commensurate increases in daily operating costs (i.e., *per diem* rates) that could affect scientist recruitment or retention by the institution. Rather than spectacular natural events, it is often a sequence of insidious, small-scale disasters such as these that compromise institutional research competitiveness and eventually undermine confidence in an animal resources program.

There are exceptions to the general rule in that the effects of a disaster event may not always be predictable (Alderson and Garnett, 2002). Facility design should investigate and account for this sort of eventuality. As an example, in 1995, with Tropical Storm Opal converging on inland Alabama and Georgia, the animal resources program at the University of Alabama-Birmingham concentrated logically and responsibly on preparing for the effects of flooding and the risks to animals in basement-level facilities (Gerrity, 1998). Although hard rains came, no buildings flooded. However, street flooding resulted in chases under the streets filling with water, cooling the associated steam lines, and causing condensation in the lines and ruptures. The physical plant ventilation system poured steam into all 10 floors of an adjacent building, including an animal research facility on the eighth floor that was deemed safe from the consequences of flooding. Temperatures in some rooms exceeded 100°F with 100% relative humidity, and several rodents died. While the UAB animal resources team responded quickly and heroically to this unforeseen event, the lesson remains: be prepared for the unexpected (Gerrity, 1998). Similarly, at Emory University, the animal resources program was prepared for the possible consequences of a millenial technology failure ("Y2K") that never materialized. However, in a random incident wholly unrelated to computer technology, steam lines in the interstitial space above the research surgery and radiology resource ruptured on New Year's Day, causing $500,000 in damage to radiology and endosurgical equipment and the building itself (authors' personal experience). At the University of Michigan in 1987, water from a burst pipe above newly refurbished faculty offices damaged equipment, out-of-print books, and years of research data and teaching materials (authors' personal experience). These disasters seemingly could have been prevented or mitigated by designing steam and water lines to be safe from flood susceptibility and away from vulnerable areas.

In the design of animal research facilities, it is important to plan proactively regarding the prevention of disasters, as many potential challenges can be programmed out at this stage. In this scenario, the key ingredients in disaster and emergency preparation are for the designers and key facility staff to predict what could happen; judge the probability that it will occur; estimate the magnitude of any unmitigated impact on operations and facilities; identify resources and/or responses that minimize or remedy the disruption; and, in doing so, create a risk index (Anderson, 1998; Vogelweid, 1998; Heath, 2000; Vogelweid *et al*., 2003).

A risk index is derived from the product of the rank of likelihood and potential frequency, duration and cost of disruptions; the rank of dependence on back-up utilities; and the cost of potential losses for all animal care and research units (Anderson, 1998; Vogelweid, 1998; Vogelweid *et al*., 2003). When renovating an existing facility, risk-indexing should include a walk-through of the facility and supporting physical plant sites with qualified members of the planning team (Vogelweid, 1998). When considering risk stratification, there are two levels that should be considered; situations that threaten science, and situations that go beyond and imperil animal or human life. The timeliness and nature of response and allocation of resources to a response may depend upon the residual level of risk after design. A blocked drain line located safely in cage-wash, for example, will imperil science and mouse breeding if the corrective intervention is extensive and loud, but will not threaten the life of adult mice. A widespread and uncontained flood due to sewage back-up or a broken pipe in the vicinity of VCS or other electrical equipment poses a life-threatening electrocution hazard for humans and animals. Failure to supply water for more than a day may confound science and, if longer, will imperil animal life. The higher the risk index, the higher should be the priority for design to prevent disasters in that area (Vogelweid *et al*., 2003).

A prudent first step in risk-indexing is to list the incidents and functional consequences that could jeopardize the facility, programs, people, animals or records, and to then predict their likelihood (Anderson, 1998; Vogelweid *et al*., 2003). While these might include susceptibility to hurricanes, tornadoes, flash-flooding, earthquakes, lightning strike or wild fires, and even the possibility of unusual hazards such as volcanic eruptions, they should be linked with functional consequences (Anderson, 1998). The two most common causes of disruption to animal care and research are a failure of infrastructure

(primary and back-up utilities, access and egress routes) and a shortage of personnel (e.g., influenza epidemics, inability to access work due to weather) (Heath, 2000). General plumbing functions that become disrupted in a disaster include excessive water, flowing antegrade or retrograde, or insufficient water; these can be manifested at the facility level or even at the cage level – particularly for rodents in solid-bottom cages. Specific examples of adverse plumbing impacts in research animal facilities include the potential everyday occurrences of burst pipes (including steam lines), clogged drains, activated fire suppression systems, oversights in the maintenance of water treatment equipment, water supply pressure-reduction failures, electrical power failures, and leaky AWS valves or bottle stoppers. They can range to unusual disruptions originating externally, such as contaminated, non-potable municipal water, or failures of institutional pumping stations. Events and situations that complicate personnel reporting to work cannot be overlooked. If the predominant method of providing water to rodents is via water bottles, then widespread absenteeism from an epidemic of communicable disease (e.g., influenza), a strike or work stoppage, or inclement weather will have a significant disruptive impact. Consequently, facility planners should be aware of environmental risks in the vicinity of the institution. Nearby chemical industries, shipping routes for hazardous materials, railways, military bases, dams, nuclear power plants and construction projects all expose the institution to potential damage and may impair staff access in the case of an accident or incident (Anderson, 1998).

In considering probability, the planning team should evaluate the history of plumbing-related disasters for the institution, and how frequently and why they occurred. Typical examples of facilities that are vulnerable to plumbing disruption include buildings that do not meet current standards of construction to withstand likely regional geophysical hazards, such as earthquakes, floods and hurricanes; those without emergency power; those with certain utility trunks or back-up generators below ground or flood level; those with aged water pipes; those with old or overloaded wiring; animal-care facilities that can only be accessed via an elevator; and small satellites in relatively remote locations (Gerrity, 1998; Vogelweid *et al*., 2003).

An estimation of the costs of disasters involves compiling an estimate of animals, supplies and research investments supported by the facility (Vogelweid *et al*., 2003). The vulnerability to catastrophic losses of humans, animals and research data can be ascertained by considering worst-case scenarios, such as from floods or prolonged power outages. The cost of disruptions and loss of data can be subjective, because it includes losses associated with death and injury of research animals, some of which may be priceless if they promise to lead to patents, progress in research and future funding and, last but not least, have the potential to contribute to fulfilling the perceived priorities of the institution (Heath, 2000). Fortunately, with respect to plumbing, most events, except for a catastrophe such as failure to exclude an external flood, will be relatively isolated in effect and will not cause damage radiating external to the institution.

If these or similar vulnerabilities to catastrophic loss are identified, then appropriate mitigation measures can be taken, for example, to appropriately build or renovate facilities, provide sufficient back-up power to support all needs, and enable redundancy of water supply or storage. This starts with a disaster-resistant facility design based upon system failure analysis (Cosgrove, 2002) in concert with design features that promote facility preventive maintenance (Heath, 2000; Vogelweid *et al*., 2003). It is important to recognize that the design factors of security, windowless construction, ventilation and centralization that drive the location of consolidated vivaria to the basements or top floors of buildings also put these animal facilities in the most vulnerable sites for damage (Cosgrove, 2002; Vogelweid *et al*., 2003, 2005). Obviously, it is critical in certain geographic areas to construct buildings to resist earthquakes and strong winds (hurricane- or tornado-proof buildings). Construction in flood plains or on slopes should be avoided or, when unavoidable, carried out with flood-proofing in mind. Exterior gutters and drains should be designed to contain and appropriately channel rainwater. When the facility is designed with a flat roof, design should ensure that water will not accumulate. Facilities should have sufficient back-up generator power (and fuel reserves) to power critical equipment including, in the case of plumbing, pumps and pressure-reducing stations. Pipes and plumbing chases should be located in areas where water leaks or back-ups from blockages can be contained or their effects minimized. In regions where severe seismic activity is likely, plumbing and other non-structural components should be appropriately buttressed and braced to remain intact (Vogelweid *et al*., 2005). Where there may be interruptions in water supply, buffer provisions should be enabled, such as water reservoirs, in the form of stored emergency bulk tanks or a repository of bottles or bags, as well as vats built into automated water treatment/distribution systems. Table 32-2 gives some examples of plumbing disaster events and corresponding design considerations.

Design should similarly enable programs of building inspection and maintenance. Chases, lines, pump rooms and interstitial space that are easy to access and service will assist in the prevention or reduction of common emergencies resulting from burst pipes, worn electrical wiring, clogged drains or other problems. Design should likewise potentiate actions to be taken if advance warning is available, such as contingency housing of essential staff on site in the face of inclement weather, stocking of water, and other preparations.

It must lastly be appreciated that some catastrophes may not be preventable or contained on the local or institutional level. For example, we live in a day and age when terrorists may act to impair entire communities, and this may have effects on research animals. If drinking water in a locality is poisoned and no longer potable, it is likely there will only be sufficient clean water made available to sustain human life and no surplus for

TABLE 32-2
EXAMPLES OF PLUMBING FAILURE RISKS

Event	Need	Design consideration
AWS cage flood	Prevent excessive water flow	
AWS animal dehydration	Maintain water and flow access	Alarmed pressure-reducing stations; continuous flow system or regular line flushing
Burst pipe	Minimize and contain flood	Alarmed water flow leak detectors, chases isolated from critical areas, drainage in vicinity
Clogged drain	Contain volume and extent of contamination	Optimal diameter (4″–6″) pipe; proper slope to drain lines and main; service access
Contamination, toxic or microbial, municipal water	Maintain animal health	Water treatment: RO + carbon filtration; back-up repository:AWS vat or stored supplies of bags, bottles or bulk tanks
Luminal biofilm	Maintain animal health	Bottled water proportioner: acidification or hyper-chlorination; AWS: continuous flow or regular flushing capability
Pump electrical failure	Maintain AWS flow	Alarmed current probe
RO filtration failure	Water of consistent quality	Failure alarm; chemical imbalance alarm
Water pressure, excessive	Maintain water flow	Water pressure alarm
Personnel homebound (weather)	Provide	Nominal water

research animals. In cases where the institutional and facility water-treatment capabilities are not adequate to remove harmful contaminants, provisions should be made, as in the case of sufficient euthanasia drugs and gases on hand, to humanely end the lives of animals at risk of intoxication or on the cusp of dehydration.

Disaster planning is essential for any institution to provide the best possible protection for animals, people, records, equipment and the facility structure. Disaster can strike at any time, often unpredictably, on either small or large scales, but if the facility has been properly designed and the institution is prepared, the damage may be decreased or avoided. Effective design based upon vulnerability assessment and enabling facility disaster resistance, prevention and response will contribute substantively to ensuring that research is safeguarded now and for the future.

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Chapter 33

Electrical: Special Considerations

Jack R. Hessler

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I. INTRODUCTION

The objective of this chapter is to highlight electrical features that require special consideration in research animal facilities. Not covered here are standard electrical engineering design features, electrical services for mechanical systems other fixed equipment per the manufacturer's specifications, and lighting other than animal rooms.

II. POWER

A. Power Outlets

Duplex receptacles with moisture-resistant covers are required to provide 110-volt outlets throughout the facility. Some equipment may require 240-volt outlets. The location of power outlets throughout the facility is critical to efficient operation, and should be coordinated with the owner's representatives. The amount of animal-care and -use equipment commonly used in animal facilities that requires power continues to increase, and can best be anticipated by those with experience working in animal facilities. Examples include ventilated racks, biosafety cabinets, data processing equipment, scales, HEPA filtered mass air displacement cabinets, physiological monitoring equipment, behavioral monitoring equipment, and sanitation equipment. A generic distribution of outlets in a small- to medium-size animal room might call for one power outlet in the center of each wall mounted 4 ft (1.2 m) off the floor. Larger rooms should have two or more outlets along the longest walls. If the room is being planned for a specific use, e.g., housing of rodents in ventilated racks,

the location of the outlets can be planned for the specific location of racks and cage-changing stations. Depending on the type of ventilated caging system to be used, one duplex receptacle may be required for each rack located high on the wall near the ceiling or in the ceiling. Special attention needs to be given to the relatively high amperage requirements for circuits servicing animal rooms with ventilated racks and biosafety cabinets. Procedure rooms where examination tables may be used should have power outlets fitted with pig-tails in the ceiling located over the tables. Power sources are also required above the necropsy and surgery tables. A preferred solution is to supply power in telescoping ceiling-mounted service columns along with surgical gases. Ground fault interrupters (GFI) should be used for every circuit in areas of the facility where water will be routinely used, which is most of the facility – certainly all animal rooms and the cage-wash area.

All penetrations in the envelope of the animal room must be sealed; this includes all power outlets, and switches. There should be minimal light switches since lights will be controlled electronically, but if there are switches in animal rooms they should be fitted with moisture-resistant covers.

B. Emergency Power

The availability of emergency power is one of the more critical requirements of an animal research facility. Extended power outages of more than a few hours at best will compromise the research being conducted in the facility. At worst, the heat load of the animals can increase room temperatures to a level that is lethal for some of the animals, starting as low as 85°F (29.5°C) for rodents and rabbits that are not heat adapted, up to most of the animals at higher temperatures. Sufficient emergency back-up power is required to maintain all essential services in the event of a main power failure. At a minimum, emergency power should include: HVAC at 100 percent capacity including sources of chilled water and steam for the HVAC system, animal housing equipment that relies on power to maintain airflow such as ventilated racks, all environmental control and monitoring systems, at least one light fixture per animal room and other life-safety lighting as required by code, the security system, the surgery room and freezers. Ideally, the emergency generator is designed to automatically provide uninterrupted power for the entire animal facility. Considering the expense of separate wiring systems to selected equipment and locations, this may also prove to be cost-effective.

III. LIGHTING

The focus in this section is primarily on the animal room. Light is a critical component of the animal's environment because it has broad and profound effects on the animal's circadian physiology. One very important example is its effect on melatonin production by the pineal gland. Melatonin has a wide array of well-documented biological effects: enhancing the quality of sleep; affecting the immune function; growth of human tumors in athymic nude rats (Blask *et al*., 2005); and affecting the uptake of essential fatty acids by human tumors in athymic nude rats (Dauchy *et al*., 1997, 2007). The lack of melatonin has even been implicated in the higher incidence of breast cancer in night-shift workers (Blask, 2005). Melatonin is produced by the pineal gland during the dark cycle, and light inhibits melatonin production. Light-sensitive cells in the retina of the eye serve as the initial conduit to nerves that signal the presence of light to the pineal gland.

To understand the facilities-related part of this complicated issue, it is necessary to have at least a very basic understanding of the physics and physiology involved. Table 33-1 outlines the visible light spectrum for humans, showing how humans perceive light at different wavelengths in nanometers. It also shows the visible light spectrum for rats and mice, which is similar to most other mammalian species; however, caution is in order when considering a particular species because there is a wide variation in the animal kingdom. Above and below these spectrums, light energy is not perceived – or at least that is what has been assumed until recently (see below). There are two types of light receptors in the retina: rods and cones. The rods are the most sensitive receptor cells, and are responsible for night vision. Cones are responsible for color vision. Of the three color receptors found in mammalian retinas (blue, green and red), most, including most common laboratory animals, have two types (blue and green). Man and Old World non-human primates and one New World species, the howler monkey, have all three.

To take advantage of this difference in the visual spectrum to create lighting conditions in which humans can see light and the animals cannot, the objective is to filter out all light up to at

TABLE 33-1

VISUAL LIGHT SPECTRUM AS PERCEIVED BY HUMANS AND ANIMALS

Light receptors	Nanometers (humans)	Nanometers (*rats and mice)
Cones (color vision)		
Violet	380–450	
Blue	450–495	459–484
Green	495–570	490–520
Yellow	570–590	
Orange	590–620	
Red	620–750	
Rods (night vision)	400–600	400–600

*While these nanometer values apply specifically to rats and mice, many mammals, including most common laboratory animals, have a similar bi-chromatic (blue–green) visual spectrum, with the exception of Old World non-human primates which have a tri-chromatic (blue–green–red) color vision spectrum similar to humans.

least the top of the visible range for most laboratory animals. Light-filtering films are commercially available for this purpose, including "Rose Chocolate 3" from Solar Graphics, "Vivarium Red" from Aegis Applied Films and Ruscikyx 26 from Rosco Laboratories. Reportedly, these films block out greater than 99 percent of the visible light up to 580 nanometers, which is well above the ability of most bi-chromic (blue–green) animals to see. In the red range that humans can sense light, the peak percentage transmission for the three products ranges from 20 percent to 80 percent. For additional information on the subject, see Chapter 7 in this book.

The use of such light filters has been the practice for many years to provide visual access to rodents during the dark cycle, presumably without disrupting the animal's circadian rhythm. One common use of this principle is red-tinting the view panels of animal room doors to block out corridor lights during the night or when the light/dark cycle is reversed. Another common use is to provide red lights in the room to facilitate work in the room during the dark cycle. Unfortunately, considering the following, this may not be adequate to avoid affecting the animal's physiology:

1. Ocular exposure to light during the dark cycle rapidly suppresses melatonin production, depending on the intensity, wavelength and duration of the light exposure (Brainard *et al*., 1983, 1997).
2. It is reported that as little as 0.1 lux decreases melatonin production (Heeke *et al*., 1999). This amount of light can leak under and around the jams of a solid door or through some, if not most, red film light filters.
3. Given that as little as 0.1 lux decreases melatonin production, the filters currently used to block more than 99 percent of the light in the rodents visible light spectrum may not be efficient enough.
4. The assumption that red light doesn't impact the animal's physiology may not be correct given the presence of non-rod non-cone light-sensitive receptors in the retina that also inhibit melatonin production.

   The non-rod non-cone receptor is the intrinsically photosensitive retinal ganglion cell (ipRGC) that functions at a lower sensitivity and spatiotemperal resolution than rods or cones (Berson *et al*., 2002). The ipRGCs communicate directly with the brain and function to encode ambient light intensity in synchronizing circadian rhythms. Indeed, other studies using blind mice (Provencio *et al*., 2000, 2002) and the blind subterranean mole rat suggest that the ipRGC is primarily responsible for circadian regulation (Hannibal *et al*., 2002).

This is a rapidly expanding area of research that merits careful attention. It may well be that current efforts to control the animal's light environment, especially during the dark cycle, are totally inadequate for the level of environmental light control required by some, if not most, studies involving animals. If so, the current practice of using red films on the doors and red night lights in the room in an attempt to achieve the goal of controlling the animal's circadian physiology may have to be reconsidered. The correct approach may be to use solid doors and light-tight jams and drop bottom seals to prevent dark-phase light contamination. In addition, standard operating procedures may need to be changed to totally avoiding entry into the animal room during the dark cycle (Dauchy, 2007). Perhaps infrared viewing goggles combined with dark-room entry doors may be part of the answer for studies that require working with the animals during the dark cycle.

View panels in doors present a dilemma. For security reasons, as well as to facilitate management of the facility, it is highly desirable to have a view panel in the animal room door. Even a shutter over the view panel that has to be opened to see into the room is not a viable solution with regard to security issues, and is not ideally suited to facilitate management, leaving the red-tinted view panels as a preferred option. For now, the animal research industry will probably stay with using red-tinted glass on animal room doors and red lights in animal rooms while keeping an eye on the mounting evidence indicating that, at least for some types of studies, the red-tinted glass may not be acceptable. The problem is not knowing for sure which types of studies may be affected by small amounts of light contamination during the dark cycle. Options for addressing this dilemma may include using a "fish-eye" peep hole in the door that is shielded when not in use. Another may include using red lights in the corridors that correspond with the dark cycle in the animal rooms, when building codes permit, in addition to red-tinted door view panels. At this time, it cannot be known if even this would adequately prevent light contamination in the animal room during the dark cycle. More studies are required to document the critical parameters required to adequately control the research animal's environment with regard to light.

C. Light Fixtures, Intensity, Color and Type

The most commonly used light source for animal rooms today is cool white fluorescent (CWF) lights. There is much written about animal room lighting (Marshall, 1991; Murphy, 2007), including the "color" emission from various types of lights, with seemingly an infinite variety available. From the standpoint of humans working in the facility, the color of light is important because it affects the ability to discriminate colors, which can be important in evaluating an animal's health status. CWF lights seem to satisfy the human eye, and data are not strong to support using lights with a different spectrum – e.g., one more similar to sunlight – especially considering the higher cost of such lights.

However, with regard to lights and energy savings, there is a suggestion supported by sound research to consider using light-emitting diodes (LED) (Heeke *et al*., 1999). The conclusion

of the study done with Sprague Dawley rats at light intensities ranging from 100 lux (9.2 foot-candles) to 0.1 lux (0.0092 foot-candles) and studying melatonin production, electroretinograms and retinal pathology was that "Light-emitting diode light appears to support normal circadian physiology and does not cause functional damage or morphologic destruction in the retinas." The phototoxicity studies involved exposure to 100 lux 12 hours per day for 14 days. The authors point out the advantages of LED lights over CFW lights to be "longer operating life, less mass and volume, less heat production, less power consumption, and higher efficiency." In addition, "LEDs can be used to produce more precisely timed and spectrally controlled photic stimuli." The current author would like to see similar phototoxicity studies at higher light levels for longer periods of time.

Phototoxicity due to light intensity in animal rooms that will house albino rodents is another complicating factor in the quest to control the animal's environment. This topic has received a great deal of attention since it was shown that the retinas of albino rodents are prone to suffering functional and anatomic damage from high-intensity light. In recognition of the phototoxic effect of light on the retina of albino animals, the *Guide for the Care and Use of Laboratory Animals* (the *Guide*; ILAR, 1996) recommends that rooms housing albino animals be approximately 325 lux at 1 m (3'3") above the floor. This level appears to be sufficient for animal care, and does not cause clinical signs of phototoxic retinopathology in albino rats after 90 days (Belhorn, 1980) and only "minimal retinal lesions" after 790 days (Weisse *et al*., 1974).

Out of concern for phototoxicity, two-staged lighting has become a common feature for animal rooms housing albino rodents. For example, the low default phase may have a light level of 325 lux (30 foot-candles) and the high light phase a light level of 800 lux (74 foot-candles) (Balk, 1980). Whether or not this is advisable or even cost-effective is a judgment call. As was noted previously, 325 lux appears to be adequate for routine animal care (Belhorn, 1980). Detailed work with individual rodents can be performed in a lighted animal transfer/procedure cabinet. There is also concern that even relatively brief periods of increased light levels can cause retinal damage in albino rodents. One advantage of installing a dual lighting system is the ability to vary the light level according to the species housed in the room. Phototoxicity resulting in retinal damage does not occur in animals with normally pigmented eyes at typical indoor lighting levels. Therefore, it would be acceptable and even desirable to provide light levels of 800 or higher for animal rooms designed to house only dogs, non-human primates or any species that has normally pigmented eyes.

Placement of light in the animal room should focus on providing a uniform light level in front of all cages at the same level in the room. In rooms with racks of cages, this requires foreknowledge of how cage racks will be parked – whether single-sided racks with the long axis parallel with and against the wall or double-sided racks parked library style with the long axis perpendicular to the wall with 30 to 36 inches between racks. Computer modeling should be considered to predict light distribution and intensity in relationship to equipment, and especially in front of cages. Even with the best possible light distribution, the light level in animal cages varies depending on the distance from the light source, which is determined by the cage location on the rack. In addition, there is a marked difference in light levels inside the cages from the back to the front, especially in micro-isolation cages.

Fluorescent light fixtures, either recessed into the ceiling or surface mounted, should be moisture-resistant with gasketed lenses and sealed at the light to ceiling junction. Surfaces of the light fixture exposed to the room should be resistant to aerosolized chemicals used to disinfect the room, including chlorine dioxide, formaldehyde and vaporized hydrogen peroxide. Light fixtures must allow for easy disinfection and re-lamping. To facilitate efficient operations, special tools should not be required to access the lamps. Some faculties with an interstitial mechanical space have animal room lights in which the lamps can be replaced in the interstitial space, eliminating the need to enter the animal room.

D. Control

As was noted previously, photoperiods influence many of the animal's biological functions. Therefore, maintaining constant photoperiods is a critical component of controlling the research animal's environment. Since windows preclude maintaining constant light levels and photoperiods, they are considered undesirable. Even windows in corridors with animal rooms are not recommended, since the intensity of outside light may be enough to affect the animals' circadian clock when removed from the lighted animal room to higher-intensity light from outside. One exception to windows in animal rooms may be non-human primate rooms, in which windows could be considered a form of environmental enrichment. Of course, it must first be determined that the lack of year-round consistency will not interfere with studies conducted in the rooms.

Automatic control of animal room lights is essential. Central control of lights with a programmable logic controller is much superior to control timers located in each room where they can more easily be tampered with and/or damaged. If dual lighting levels are provided for rodent rooms, the low level should be the default level and the high level should be controlled with a timer switch located near the door, either inside or outside the animal room. The quality of such switches varies greatly, and the most reliable should be used. The switch should allow for a variable time period of up to 1 hour, after which the light level automatically changes back to the low level. The high-level timer switch should be programmed or wired to render it inoperable during the programmed dark cycle. If the rooms house only animals with pigmented eyes, the light levels could be centrally controlled at the high level during the light cycle, bypassing the timer switch located at the room.

A typical light cycle is 12 hours on and 12 hours off, but each room requires individual light-cycle control since certain studies may require alternative cycles, including reverse cycles. White lights should never be turned on during the dark cycle. If darkroom lighting is to be installed in the animal room, the level of the light should be carefully considered based on the information presented at the beginning of this "Lighting" section regarding the effects of even very low-intensity light. Dark-cycle lighting could vary from one or more 25-W bulb fixtures with an Eastman Kodak 1 A safelight filter, to a fluorescent light fixture with the lenses covered with one of the red films noted previously in this chapter and other chapters in this book. The question is: considering both time and intensity, when is a little red light too much? Unfortunately, the answer is not known but, as discussed above, it may be much less than previously thought. If red light is provided to a room, it should be controlled in the same way as the dual white-lighting system described above, with an on switch at the room and an automatic switch that turns the light off after a variable period up to 1 hour.

IV. COMMUNICATION

Telephone, Internet connection and local intercom communication need to be considered. The location of each may vary with the complexity of the facility, and should be worked out with the individuals who will be managing and working in the facility. Telephones are recommended in all offices, laboratories and animal procedure areas. Data ports are recommended in all the same areas plus the animal rooms unless wireless technology is made available. Intercoms with speakers in every room at one time were considered highly desirable for communication within the facility. Some consider the intermittent and loud sound (noise) of their use may be stressful to some animals, while others consider background music to provide a valuable "white noise" background that partially mitigates the stress of sounds produced when working in the room. Other technology, including cell phones and similar devices, could more effectively provide intra-facility communication, but care must be taken to ensure that cell phones work inside the animal facility.

The environmental control system will of course require considerable wiring in the facility. Wiring may also be required for a totally redundant environmental monitoring system that may have monitoring sensors (temperature, relative humidity, light, airflows, relative air pressure, etc.) in every animal room and at multiple pieces of equipment (automatic watering, autoclaves, cage washers, etc.) with flat-screen monitors throughout the facility.

V. CONCLUSION

Electricity is the single most important ingredient in the mix of ingredients required to control the research animal's environment. Nearly every aspect of animal care and use relies on it, making the availability of emergency power a must for contemporary research animal facilities. High on the list of demands for uninterrupted electrical service is the HVAC system, including chilled water, and all equipment and activities directly related to the animals well-being and homeostasis. The list is so extensive that the most cost-effective approach may be to provide emergency power for the entire animal facility. Controlling the animal's light and dark environment proves to be one of the most complicated and problematic issues, given recent data indicating that very low-intensity light (<0.1 lux) can decrease melatonin production and confound the results of animal studies. The discovery of intrinsically photosensitive non-rod non-cone light receptors in the retina that are capable of influencing the animal's circadian cycle further complicates the issue. Ongoing studies to better understand control of melatonin production and circadian rhythms merit close attention. As knowledge regarding this critical issue unfolds, design criteria for controlling the animal's light environment will need to evolve with it in order to meet the demands of contemporary research.

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Chapter 34

Heating, Ventilation and Air Conditioning (HVAC): Special Considerations

Jack R. Hessler and Daniel P. Frasier

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I. INTRODUCTION

The animal facility HVAC system is the most critical, complex and expensive component of today's laboratory animal facility. The primary function of the HVAC system is to stabilize the laboratory animals' macro-environment (the room) and micro-environment (the cage), and maintain a comfortable and healthy work environment for personnel. Specifically, the function of the HVAC system is to control ventilation, temperature and humidity within specified ranges, and remove

airborne particulates (including microbes) and gaseous contaminants generated in the animal room. Many general animal facility-related references include descriptions of HVAC systems (Ruys, 1991; Veterans Administration, 1993; Hessler, 1999; Hessler *et al*., 1999; Hessler and Höglund, 2002; Hessler and Leary, 2002; CCAC, 2003; NIH, 2003; Lipman, 2007). A few publications have specifically addressed HVAC systems for animal facilities (Neil and Larsen, 1982; Hessler and Roberts, 1988; White, 1991; Kowalski *et al.*, 2002; Mowinski and Johnson, 2005). The American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE) has recognized the unique design requirements of HVAC systems for research animal facilities and includes a separate section, "Environmental Control for Animals & Plants," in its *ASHRAE Handbook, HVAC Applications* (ASHRAE, 2007).

II. AIR QUALITY

The source and extent of filtration determine the quality of the air supplied to a facility. The location of fresh air intakes must be carefully considered to avoid re-entrainment of exhaust air from other buildings or the same building, especially the animal facility itself, and from incinerator smokestacks, vehicle and emergency generator exhaust fumes, etc. Wind wake analysis can be a useful tool in anticipating and avoiding re-entrainment (Figure 34-1).

The degree to which incoming air is filtered varies with the type of animal facility and the facility's program requirements. Supply air filter efficiency for research animal facilities typically varies from 85 percent to 99.97 percent high efficiency particulate air (HEPA) filters, with 95 percent generally being considered the most cost-effective. HEPA filtering incoming air may be considered ideal, but the need for delivering HEPA filtered air to the entire animal facility, or even special sections such as a rodent barrier, is not well documented and its cost-effectiveness is questionable. Task-directed HEPA air filtering may be more cost-effective – e.g., ventilated rodent cages and cage-change cabinets.

HEPA filtering mass quantities of air recirculated within individual animal rooms was considered the ultimate answer to animal disease control from the early 1970s to the mid-1980s. Such systems were referred to as "mass air displacement (MAD) clean rooms," or just "clean rooms." In MAD clean rooms, air is recirculated within the room through HEPA filters at volumes sufficient to change the air from 150 times per hour (with remote HEPA filters) to 600 times per hour (with a complete ceiling of HEPA filters). Fresh air exchanges are superimposed over the recirculated air in quantities required to handle heat loads, which are the usual animal- and room-related loads plus that generated by the MAD system. MAD clean rooms effectively control the animal's airborne microbial environment, thereby reducing cross-contamination between cages. These may be either built-in "hard wall" or free-standing "soft wall" units the size of rooms large enough to house multiple cage racks, or just large enough to house a single cage rack. Some MAD rooms are still in use, but interest in installation of new hard-wall units has waned. Recently there has been a renewed interest in using multiple soft-wall MAD clean room units placed in large rooms – even in large warehouse-type spaces – to gain maximum flexibility for isolating groups of animals at minimal cost (Figure 34-2).

III. VENTILATION

Air handlers and exhaust fans should be dedicated to the animal facility. Air handlers should be controlled to automatically adjust fan speed to account for changes in static pressures due to factors such as filter loads. Air supplied to animal facilities should be 100 percent outside air (i.e., 100 percent fresh makeup air with no recirculation). The ventilation rate recommended for animal rooms, expressed in terms of air changes per hour (ACH), varies from 10 to 20. The *ASHRAE*

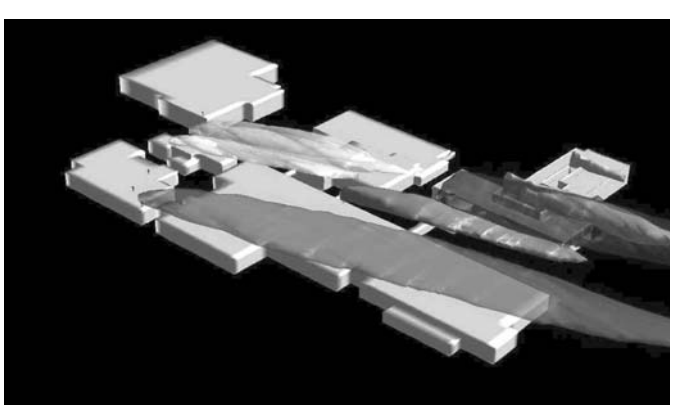

Fig. 34-1 Wind wake analysis shows iso-surfaces of different gases.
Figure courtesy of M/E Engineering, PC-The CAES Group.

Fig. 34-2 Multiple HEPA-filtered mass air displacement flexible film "rooms" inside a large room.
Figure courtesy of bioBubble, Inc.

Handbook (ASHRAE, 2007) recommendation is 10–15 ACH, with 15 probably being the most commonly used rate; however, there is no hard and fast rule regarding a minimally acceptable ventilation rate. Engineering calculations should be done to determine the optimal ventilation rate based on heat loads, local exhaust device airflows and ability to maintain barrier or containment requirements. Once the ventilation system has been sized, designed and installed, the goal is to maintain adequate control based on environmental performance standards measured as the cooling load and microbial, airborne particulates and gaseous contaminants generated in the room (ILAR, 1996).

From an occupational safety and health perspective, controlling animal allergens is paramount. The most common occupational hazard for personnel working with research animals is exposure to animal allergens and subsequent sensitization to these. Controlling the heat load in the room is the primary concern from a science and animal welfare perspective. Room temperatures above 85°F (29.4°C) can be life threatening to laboratory rodents not adapted to such temperatures (Gordon, 1990) and sub-lethal high temperatures, along with wide fluctuations in room air temperatures, can stress rodents and other species to the point that studies will be compromised (Garrard *et al*., 1974; Gordon, 1993). It is important to keep in mind that if micro-isolation caging is used, the temperature in the animal's micro-environment (cage) can be several degrees higher than in the macro-environment (room). The predominant gaseous contaminant is ammonia, which is generated by urease-positive bacteria from the feces splitting each urea molecule from urine into two ammonia molecules. Ammonia production depends on many factors, including the density and gut microflora of the animals in the cage, the type of bedding, the sanitation level, and the relative humidity in the cage – the lower the relative humidity, the lower the rate of ammonia production and *vice versa* (Briel *et al*., 1971; Kruckenberg, 1971; Hasenau *et al*., 1993; Memarzadeh, 1999).

As a general rule, a ventilation rate that adequately controls the heat load of a room housing the maximum capacity of rats when the air handler discharge temperature is at a minimum 55°F (12.8°C) has proven to control gaseous contaminants adequately; however, airborne allergens may not be controlled adequately to protect personnel sensitive to the allergen. One advantage of negative-pressure ventilated rodent caging that exhausts the air from the cages directly to the building's exhaust system is that these effectively prevent particulate and gaseous contaminants generated in the cages from entering the macro-environment. Negative-pressure ventilated caging systems that HEPA filter the air returned from the cages to the room significantly reduce, and may even eliminate, animal-related allergens and other airborne particulate contaminants from entering the macro-environment, but do not reduce gaseous contaminants. Positive-pressure ventilated caging systems that typically supply approximately 10 percent more air to a cage than is exhausted from the cage do discharge some particulates, including allergens and gaseous contaminants, into the macro-environment; however, the quantity is significantly reduced if the remaining 90 percent of the air from the cages is either HEPA filtered or discharged directly into the building exhaust system.

Air exhausted from conventional animal rooms is often fitted with coarse disposable filters at the room exhaust air outlets to protect the exhaust air ducts and heat recovery coils. The exhaust outlets should be designed to facilitate viewing and changing the filters. The filters may be fully exposed and unprotected to achieve this objective. Exhaust air filtration from biocontainment spaces rated higher than Biosafety Level 2 (BSL2) usually include HEPA filters.

A. Ventilation and Animal Room Heat Load

In addition to the usual heat load calculated for generic spaces and the heat load generated by the animal, heat-load calculations must include heat generated by animal-care equipment that will or may be used in the room, such as biosafety or cage-change cabinets, and fan/filter modules for ventilated cages (note that some ventilated racks have two; one for supply air and one for return or exhaust air). Equipment manufacturers can provide heat loads generated by their equipment. Ventilated micro-isolation caging that exhausts air from the cages directly into the facility exhaust system may effectively reduce the animal heat load in the room by 20–33 percent. The lower percentage was determined by a cage manufacturing company based on physical measurements of ventilated cages (personal communication), and the higher is based on computational fluid dynamics studies (see Chapter 35 in this book). The remaining animal heat load dissipates across the cage by convection and radiation into the room, and must be included in the total room sensible heat-load calculation. Heat loads for various species of animals are listed in the *ASHRAE Handbook* (ASHRAE, 2007). If the species that will be housed in the room is unknown and may vary from mice to dogs and non-human primates, the design calculations should be based on a maximum capacity of rats, since that will generally represent the highest possible animal-related heat load that may be housed in the room.

B. Variable Air Volume (VAV)

Constant air volume has long been the standard for animal facilities. VAV systems for animal rooms designed to automatically maintain established set-points for room temperature, relative humidity and air quality by adjusting airflow based on actual loads should theoretically be ideal for animal rooms with variable animal populations and equipment, since these spaces have variable heat, airborne particulate and gaseous contaminant loads. Even with a VAV system, a minimal base should be established for air changes (e.g., eight changes

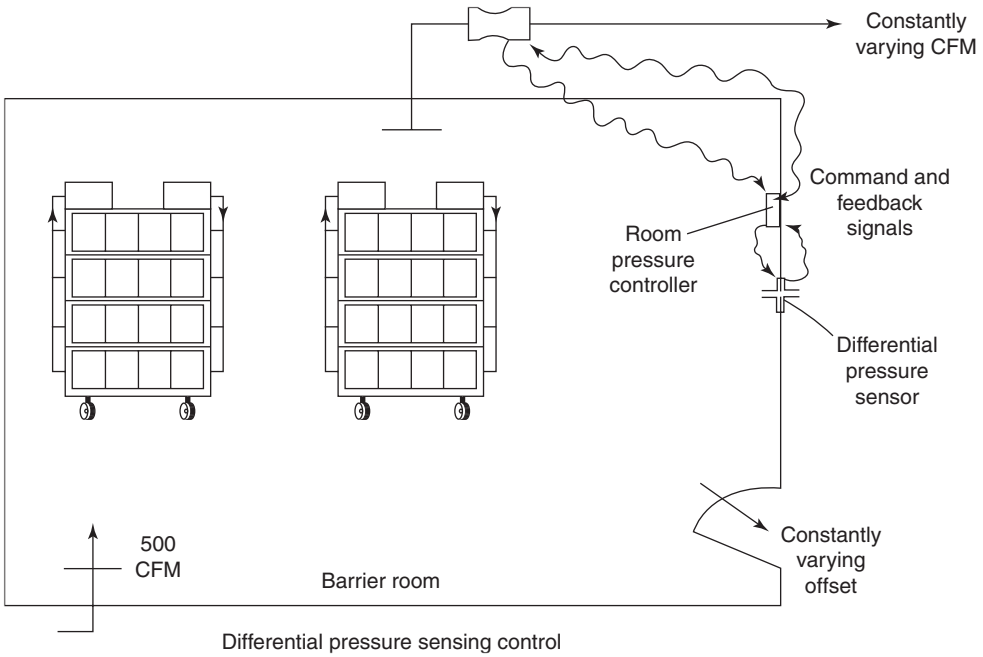

Fig. 34-3 Active pressurization method of controlling room directional airflow.
Figure courtesy of Phoenix Controls Corporation.

per hour to control particulate airborne contaminants); however, in rooms with ventilated racks, the base may be lower and based entirely on heat load. This would be an example of using performance standards to determine what would be an adequate ventilation rate, an approach that is encouraged in the *Guide for the Care and Use of Laboratory Animals* (the *Guide*; ILAR, 1996). The most significant benefit would be energy conservation any time the density of animals housed in a room is less than maximum design load. Presumably this would also apply to particulate and gaseous contaminants, but not necessarily. The same applies to other rooms in the facility, such as the cage sanitation area where loads range from very high when the sanitation equipment is being used to very low or even off when it is not in use. New, more reliable control and monitoring systems have been tested and proven, making VAV for animal facilities more common, even somewhat standard. If VAV is used, high-performance air valves are required to provide reliable repeatability over time. A more basic and possibly more reliable form of VAV has been described (Mowinski and Johnson, 2005) that provides the capability to switch between a high fixed ventilation rate and a lower fixed ventilation rate (e.g., 15 air changes per hour and 10 or 8 air changes per hour). As described, this is done by providing two-position air valves in both the supply and exhaust air ducts, with control of the air valves not being automatic but switched manually only by selected personnel. VAV applications are also useful for switching pressurization between positive and negative, increasing airflows to purge rooms after decontamination, and to reduce flows in non-critical rooms during emergency power conditions to allow holding rooms and others to stay at normal ventilation rates. Proper set-up and verification is required to ensure proper performance of VAV systems.

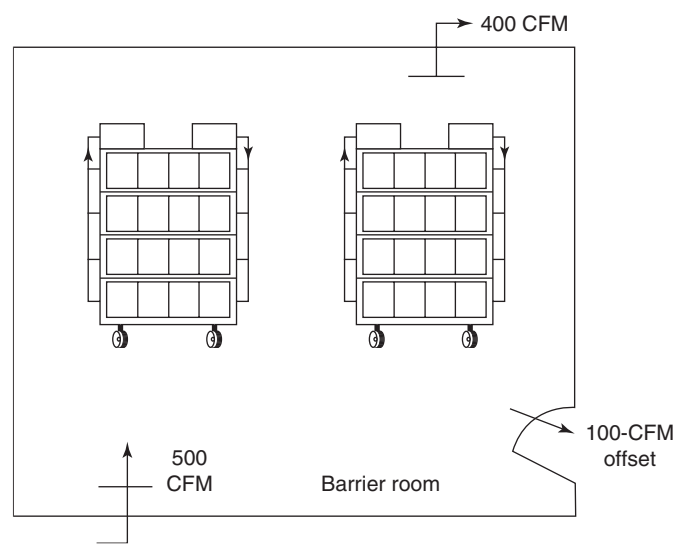

Fig. 34-4 Volumetric offset method of controlling room directional airflow.
Figure courtesy of Phoenix Controls Corporation.

C. Pressurization and Air Balancing

As noted previously, another critical function of the ventilation system is to control airborne contaminants by maintaining appropriate relative air pressures throughout the facility (Hessler, 1991; Hessler *et al.*, 1999). The two most common room pressurization methods for laboratories are active pressurization and volumetric offset control (Figures 34-3 and 34-4). Active pressurization is done by monitoring the pressures between a space and reference point, sometimes an adjacent corridor or, less often, a common reference point

for the entire facility or suite of rooms. Active pressurization is achieved by controlling either the lab's total supply or its exhaust to a constant flow, and then modulating the other to maintain a differential pressure set-point. Volumetric offset, on the other hand, is done by controlling the supply or exhaust to a fixed difference above or below the other. For example, in a negatively-pressured room, the total room supply flow might track 100 cfm less than the total room exhaust flow. Either method can be used to control supply and exhaust throughout the facility to create pressurization zones (e.g., biocontainment, barrier, quarantine, cage sanitation areas), but the volumetric offset method is much more common due to the inherent stability during balancing and into the life of the facility. It is also an industry-recognized recommendation to use volumetric offset in most lab applications. An ANSI Z9.5 clarification memo in the *ASHRAE Handbook* states that, "specifying quantitative pressure differential is a poor basis for design. What really is desired is an offset air volume" (ANSI/AIHA Z9.5, 2002). Active pressurization is most common in facilities where multiple levels of cascading pressures are required, and where facilities personnel can make reliable control loop adjustments over time. Proper balancing is dependent on two factors: proper sealing of the room envelope, and installing reliable mechanical equipment and control systems designed to maintain the appropriate volumetric offset between supply and exhaust air to achieve adequate differential pressures, typically from 0.03–0.075″ (0.08 to 0.2 cm) of water column. The higher levels are preferred for biohazard and quarantine areas. In modern facilities, a volumetric offset approach is used to control air balance in a space. This involves monitoring and controlling supply and exhaust airflows for each room, typically with pressure-independent airflow control valves (PICV). These may be either mechanical venturi devices, such as the Phoenix Controls valves, or various types of modulating dampers and air bladder valves electronically controlled by feedback from airflow sensors in the air duct. The advantage of these high-performance airflow control valves is the ease of reversing pressurization in a room, if this is a priority. Proper air balance is important in controlling contaminants, but even balancing has its limitations. Most significantly, the differential air pressure becomes zero between spaces on either side of an opened door, allowing airborne contaminates to randomly move freely between the spaces (Keene and Sansone, 1984).

Relative air pressures in animal rooms of a single-corridor facility are dependent on how the facility will be managed: conventional, containment or barrier. Table 34-1 summarizes various animal room air-balance options, depending on facility type and circulation pattern. In a single-corridor conventional facility, the animal room air pressure may be balanced positively or negatively to the corridor. Typically, rooms are balanced negative to the corridor to reduce animal allergens and odors in the corridor, thereby creating a more pleasant work environment and reducing personnel's exposure to animal allergens. In a conventional facility housing both "clean" and "dirty" animals, rooms with "clean" animals may be managed as a barrier. In this case, these rooms would be balanced positive to the corridor. For this reason, the ability automatically to reverse room air pressure relative to the corridor without rebalancing the entire system is a highly desirable feature in a single-corridor conventional animal facility. In a single-corridor containment facility, where the objective is to contain airborne contaminants, the relative air pressure in the animal rooms will be balanced negative to the corridor. The opposite does not necessarily hold for a single-corridor barrier facility, where the choice depends more on management philosophy. One philosophy calls for balancing animal rooms positive to the corridor in an effort to keep airborne contaminants out; the other calls for balancing animal rooms negative to the corridor on the assumption that if a break were to occur, the infectious agent would be contained in the room in which it occurred until detected and eliminated. Both management philosophies have merit, and neither is clearly right or wrong. However, one advantage of the latter is that it maintains corridors relatively

TABLE 34-1

Balancing Ventilation
Relative Air Pressure Between Corridor and Animal Room: Positive Pressure, Air Flows From Corridor → to Room; Negative Pressure, Air Flows to Corridor ← From Room

	Single corridor	Dual corridor	
Managed as a:		Clean	Soiled
Conventional facility	+ or −	+	−
Barrier facility	+or−	+	−
Containment facility	−	+	+ or −

+ , Corridor positive to animal room − , Corridor negative to animal room

+ or − in a single-corridor conventional facility

In a conventional facility, relative air pressure in the corridor is generally maintained positive to the animal rooms. Exceptions are facilities with mixed "conventional" and "barrier" rooms, where the air pressure in the barrier rooms is maintained positive to the corridor and negative to the corridor in the conventional rooms. The air pressure in rooms that contain hazardous agents must be negative to the corridor.

+ or − in a single-corridor barrier

Both options are used. Following is a rationale for each.

- **Corridor negative to animal rooms –** to keep airborne contaminants out of the room
- **Corridor positive to animal rooms**
  1. Infectious agents of concern are not ordinarily present in a barrier facility, so the rationale "to keep airborne contaminants out of the room" does not apply as in a mixed facility.
  2. A "break" will occur in an animal room in the barrier at some time. When it does, the management objective must be to contain the infectious agent, like in a biocontainment facility, until it can be detected and eliminated from the room and the barrier.
  3. Keeping air pressure in the corridor positive to the animal room has the additional benefit of reducing animal allergens and odors throughout the facility.

+or − in a soiled corridor of a double-corridor containment facility

Both options are used for the soiled corridor. Negative pressure is more common, but positive may be preferred in some situations.

free of animal allergens, which are well documented as a serious and common occupational hazard (ILAR, 1996; Reeb-Whitaker and Harrison, 1999).

In dual-corridor facilities, regardless of facility type, relative air pressures are typically balanced with the clean corridor positive to animal rooms and animal rooms positive to the soiled corridor; however, in some instances both corridors may be positive to the animal rooms.

D. Special Ventilation Considerations

1. *Cage Sanitation Area Considerations*

The cage sanitation area and the cage sanitation equipment have critical ventilation requirements that require careful consideration. The most basic requirement is a dedicated exhaust system. Cage sanitation equipment uses water at a temperature of 180F (82°C) or higher, generating large quantities of hot, moist air to be exhausted directly from the equipment and from the room. In addition to hard-ducting to the washing equipment, exhaust canopies are required at the entry and, most importantly, exit ports of the washers to capture the large amounts of hot moist air that flow from the wash equipment when the doors are opened. The objective is to exhaust the air to the outside with minimal cooling to keep the amount of condensation to a minimum. Air from the cage sanitation area should not be mixed with exhaust air from the rest of the facility because the relatively cool air will greatly increase the amount of condensation. The dedicated exhaust system, including the ducts and canopies, should be constructed of rust-proof and acid-resistant materials, typically welded stainless steel. The exhaust ducts must be sealed to prevent water leakage, and sloped to drains located at low points on the ducts to dispose of condensate that will form in the ducts. Of course, the overall ventilation requirements of the room must take into consideration the enormous heat and moisture load in a room that may include a significant mass of stainless-steel equipment that will exit the washers at temperatures of 180°F (82°C) or higher to be cooled to room temperature. The key features of cage-wash area exhaust are:

1. Welded stainless-steel canopy hoods with troughs on the bottom perimeter. The bottom of the canopy should be pitched to a low point and include a drain connection (welded threaded coupling) to connect a drain pipe to avoid build-up of water in the trough, which can become a breeding area for mold and mildew.
2. Canopy locations, which should be coordinated among the contractors, manufacturers and owners.
3. A welded stainless-steel exhaust duct, which is pitched to a low point with a drain large enough to prevent condensate from collecting in the horizontal ducts.
4. Exhaust connection balancing, which should be coordinated among the tunnel- and rack-washer manufacturers to confirm these hard-ducted connections have been adjusted to flows that allow the equipment to operate properly. Too much exhaust limits the ability to maintain appropriate water temperature in the washers; too little causes condensation to drip or pour out onto the floor.

A desirable but somewhat costly feature is a condensate coil installed in the vertical exhaust duct directly above tunnel- and rack-washers. These coils have chilled water flowing through them during operation of the washers to strip moisture out of the exhaust duct, from where it drains back into the washer chamber. Condensate coils with corrosive-resistant coatings, such as baked phenolic, can be provided by the washer manufacturers as an accessory.

The liquid discharge from cage-wash and autoclave equipment must meet the temperature requirements of the local wastewater authority. Compliance with the local waste department may require mixing the liquid waste with chilled water or non-potable cold water to reduce the temperature enough for discharge, to below the limits for the city sewer.

2. *Biocontainment Considerations*

Room air exchange rates may be elevated beyond the 10–20 changes per hour typically used (e.g., up to 100 ACH) when controlling airborne particles is a high priority. Higher air-change rates should not create excessive air velocities, which generate cross-drafts in areas where equipment such as biosafety cabinets, fume hoods and downdraft tables is used. Proper selection of diffusers is essential to prevent this problem. Even when not required by guidelines or regulation, HEPA filtration of exhaust air from biocontainment areas and any areas or rooms potentially generating hazardous airborne particulates is highly recommended for public relations reasons. This will require having a dedicated exhaust system for the rooms and areas involved. Other HVAC features to be considered, but that may not be required, include bioseal or other types of tight dampers to automatically isolate room supply air from the remainder of the supply system when the containment exhaust system is inoperable. Parallel air stream "bag-in bag-out" HEPA filters with a totally redundant exhaust system may be used to maintain exhaust airflow when filters are being changed or when exhaust fans are shut down for maintenance (Figure 34-5). For high-level biocontainment, redundancy of the exhaust system is a must. For more details, see Chapter 25 in this book.

3. *Special Ventilation Considerations for Fixed and Mobile Equipment*

a. Fume Hoods and Biosafety Cabinets

Fume hoods and certain types of biosafety cabinets are common pieces of fixed equipment with special ventilation requirements that are not unique to animal facilities. Autoclaves are

Fig. 34-5 Redundant bag-in/bag-out HEPA filters.

Fig. 34-6 Supply and exhaust filter/fan modules for a ventilated rack sitting on a wall-mounted shelf.

also not unique to animal facilities, but materials routinely autoclaved in animal facilities may be, in that these often result in exceptionally high odor levels. Because of this, particular attention is required to provide exhaust system canopies configured and designed with sufficient airflow to capture the heat, moisture and odors emanating from the autoclave chamber when the door is opened. The canopy features should be similar to the canopies for the cage sanitation area.

b. Ventilated Rodent Racks

Ventilated rodent racks are an example of equipment that may benefit from a direct connection to the ventilation system, although it is not required. Chapter 20 in this book includes a detailed description of ventilated cages and cage racks. Ventilated racks may be totally independent of the building HVAC system, with self-contained fan/filter modules blowing HEPA filtered air directly into each cage on the rack. The air from the cages may flow from the cages back into the room, or it may first be captured and HEPA filtered by a second fan/filter module before being blown back into the room (see Chapter 20, Figure 20-15). The fan/filter modules can be mounted on cage racks or in a separate mobile floor stand, but ideally are mounted on wall shelves and connected to the racks with flexible ducting (Figures 34-6 and 20-11). This reduces the transmission of vibrations to the cages and reduces the ergonomic hazards involved with transferring the fan/filter modules from rack to rack when racks are rotated for sanitation. With either configuration, the only special HVAC consideration is the heat load of the fan/filter modules.

HEPA filtering the exhaust air from the cages before returning it to the room removes particulate contaminants, but does not remove gaseous contaminants and heat. This is best accomplished by coupling the rack exhaust to the room exhaust. There are many strategies for integrating both supply and exhaust air of ventilated racks with the ventilation system (Lipman, 1993; Bilecki, 2001; Hessler and Leary, 2002; Lipman, 2007; Chapter 20 in this book). Regardless of the strategy selected, it is important to decide early in the planning process, since the design of the room ventilation system must be matched with the equipment to gain maximum benefit. Not only does the decision affect the physical couplings; it also impacts the cubic feet of air per minute (cfm) of supply air required in the room and exhaust air from the ventilated rack. For example, rooms with self-contained fan/filter units that return rack exhaust air to the room require higher air-exchange rates than rooms that directly exhaust a portion of the heat load generated by the animals and fan/filter units directly out of the room. As noted previously, ventilated micro-isolation caging that is exhausted directly from the cage into the facility exhaust system may effectively reduce the animal heat load in the room by between 20 and 33 percent; however, the remaining animal heat load is dissipated across the cage into the room by convection and radiation, and must be included in the total room heat-load calculation.

A common airflow requirement for ventilated racks is 0.2–0.3 cfm per typical mouse cage with a capacity of up to five adult mice. This produces approximately 55–80 in-cage air changes per hour. However, the actual amount required per cage will vary depending on the cage size and rack manufacturer. The number of mouse cages per mobile rack typically ranges up to 140 cages, but fixed racks may have even more.

Contemporary facilities designed to house a large number of rodents in ventilated caging often couple the ventilated racks

with the facility HVAC system. In the options listed below, the following acronyms, definitions, or symbols apply:

FSS = facility's air supply system
FES = facility's air exhaust system
FFM = fan/filter module (HEPA filter)
FD = flexible duct
Rack/cage = rack supply plenum – cage rack exhaust plenum.
PICV = pressure-independent airflow control valve
→ = direction of airflow.

Following is a brief description of six configurations for coupling ventilated racks with the facility HVAC system, starting with the source of air to be supplied to the ventilated cages. The advantage of the four configurations using room air as the source is that the room serves as a mixing chamber for tempering the air temperature before it is supplied to the ventilated cages.

- *Option 1.* From room air → supply FFM → rack/cage → exhaust FFM → FES via a thimble connection (Figures 34-7 and 20.17). Notes: The primary advantage of this configuration is its simplicity in terms of HVAC design because the rack air supply and exhaust are self-balanced by the supply and exhaust FFMs for each rack. All that is required are strategically placed thimble exhaust ports for each rack. Other advantages are the ability to filter air from the cages in the FFM before it is discharged into the FES and the reliability of local exhaust for higher containment applications, such as ABSL3. The exhaust FFM need not be equipped with a HEPA filter; a relatively coarse filter is adequate to protect the FES from excessive dust, unless for ABSL3 exhaust, for which HEPA exhaust is usually required. The primary disadvantage is the cost of two FFMs for each rack or pair of racks, depending on the manufacturer. The noise, vibration and heat load generated in the animal room by the FFMs are relatively minor and manageable disadvantages. Using a thimble connection instead of a hard duct avoids the possibility of pressurizing the exhaust system.

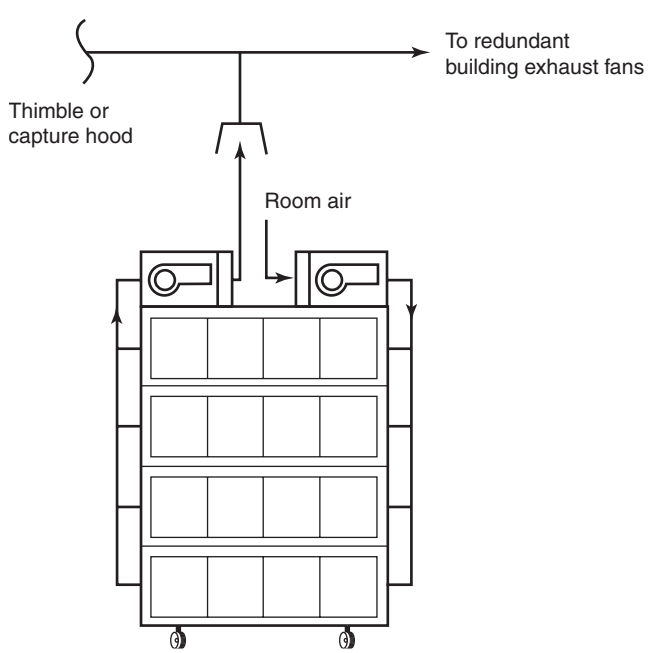

Fig. 34-7 Option 1: supply – room air via filter/fan module for each rack; exhaust thimble (decoupled) connection to building exhaust.
Figure courtesy of Phoenix Controls Corporation.

- *Option 2.* From room air → supply FFM → rack/cage → hard ducted to FES with a PICV controlling airflow from each rack (Figures 34-8 and 20-16). **Notes**: The PICV is required to assure a constant flow of air from the rack regardless of pressure fluctuations in the building exhaust, such as may occur because of increasingly dirty filters, slipping fan belts, or disconnecting of other racks from the system. Alternatively, one PICV could be provided for several racks and the airflow balanced between the racks with manual balancing dampers. In this case, load simulators that mimic the pressure drop across the rack must be used when the rack is disconnected.
- *Option 3.* From room air → a larger FFM supplying room air to multiple racks in the room → PICV controlling flow to each rack → rack/cage → hard ducted to FES with a PICV controlling airflow from each rack (Figures 34.9 and 20.22). **Notes**: An alternative is to provide two PICVs (one for supply and one for exhaust) for a group of racks (e.g., three racks) and balance the air to and from the racks with manual balancing dampers. To maintain balance in this case, a load simulator with resistance values equal to that of the rack must be inserted on both the supply and exhaust flexible ducts when a rack is disconnected. Ideally, the FFM would be located in the overhead space. The advantages of this option are reduced noise in the holding rooms, and fewer FFMs to maintain. Even if the FFM is in the overhead space, sound attenuation in the duct between the FFM and the FD to the rack should be considered. Ideally, a redundant supply fan/filter unit would be installed to automatically provide backup air supply to the racks in the event that the primary unit fails. At a minimum, a complete back-up unit should be readily available for immediate replacement or repair.
- *Option 4.* From room air → through filter on cage → cage → through filter on cage → rack plenum → hard ducted to FES (Figure 34.10). **Notes**: This is a significantly different configuration from the other five options in that it has no extraneous fans and requires nothing more than a connection to the room exhaust. It typically relies entirely on the negative pressure in the exhaust duct to generate airflow through the cages; however, a balancing damper or PICV could be placed between the

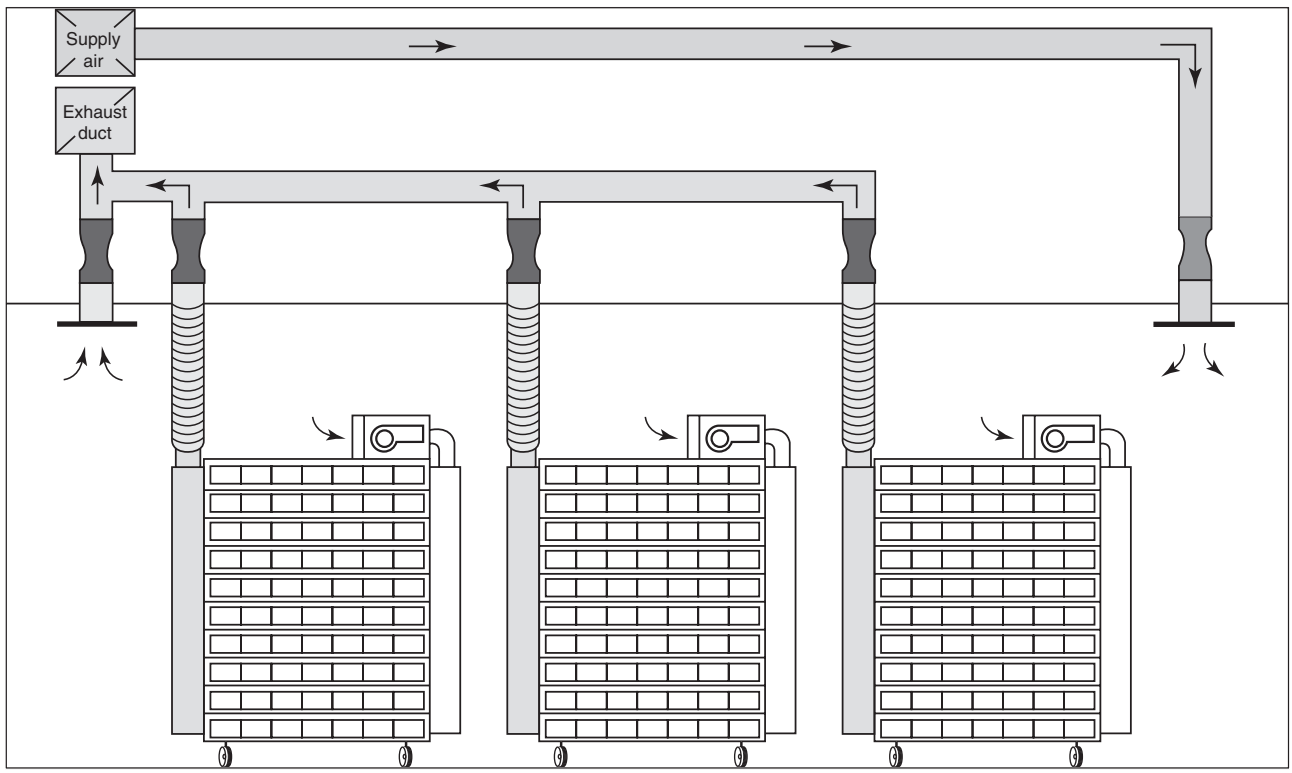

Fig. 34-8 Option 2: supply – room air via filter/fan module for each rack; exhaust – hard-ducted to building exhaust. Exhaust airflow for each rack is controlled automatically by a pressure-independent control valve.
Figure courtesy of Phoenix Controls Corporation.

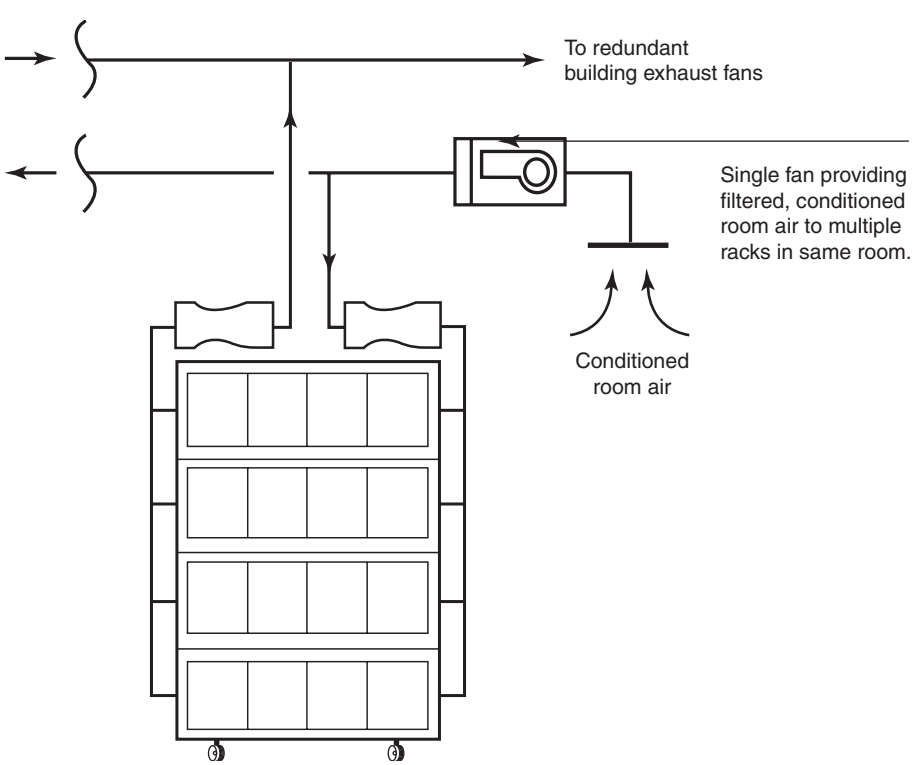

Fig. 34-9 Option 3: supply – room air via common filter/fan exhaust module supplying air to multiple racks in room; exhaust – each rack hard-ducted to building exhaust with airflow controlled automatically by a pressure-independent control valve.
Figure courtesy of Phoenix Controls Corporation.

rack and the exhaust duct to assure a maximum airflow. A load simulator is required when a rack is disconnected from FES. At this time, only one cage manufacturer uses this approach to ventilated cages.

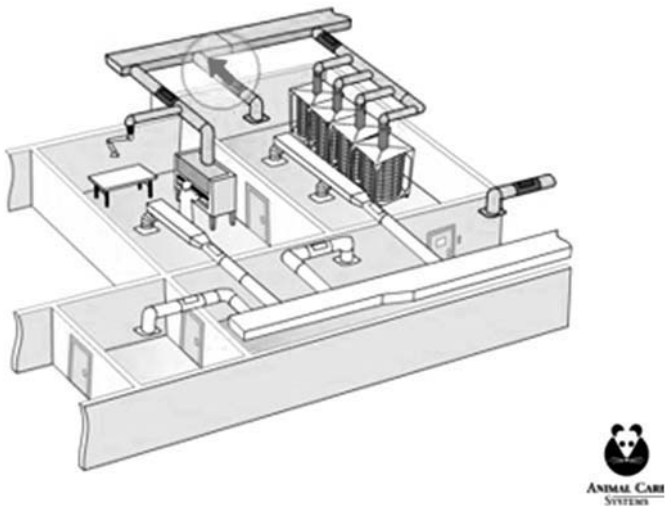

Fig. 34-10 Option 4: supply – room air; exhaust – hard-ducted to building exhaust. Airflow for each rack is controlled with either an automatic pressure-independent valve or a manual balancing damper. The building exhaust system pulls air from the animal room through filters into the cage, through the cage, through the rack exhaust manifold into the building exhaust system.
Figure courtesy of Animal Care Systems.

- *Option 5.* Directly from FSS → branch duct to each room dedicated to supplying air to ventilated racks in each room PICV → terminal reheat → manual balancing damper to each rack → rack/cage → manual balancing damper from each rack → branch exhaust duct receiving air from all the racks in the room → PICV → FES (Figure 34-11). A better, but more expensive, alternative would be to have a PICV valve controlling airflow to and from each rack (see Figure 20-23). **Notes**: If the objective is to supply HEPA-filtered air to the animal cages, this configuration requires that all air to the facility be HEPA filtered. The air temperature delivered to the room from the FSS is too low to be delivered directly to the cage, so a terminal reheat is required in the branch duct delivering air to the ventilated cages. It should be a low-temperature hot-water reheat with a variable solenoid valve to maintain as little variation in supply air temperature as is practical – no more than ±1°C and preferably ±0.5°C. The solenoid valve must default in the closed position to preclude overheating the air delivered to the animal cages. As described above in the third option, a modification would be to provide one PICV for a group of racks and balance the air to and from the racks within the group with iris dampers.
- *Option 6.* From dedicated air handler → all ventilated racks in the facility. This configuration would look much

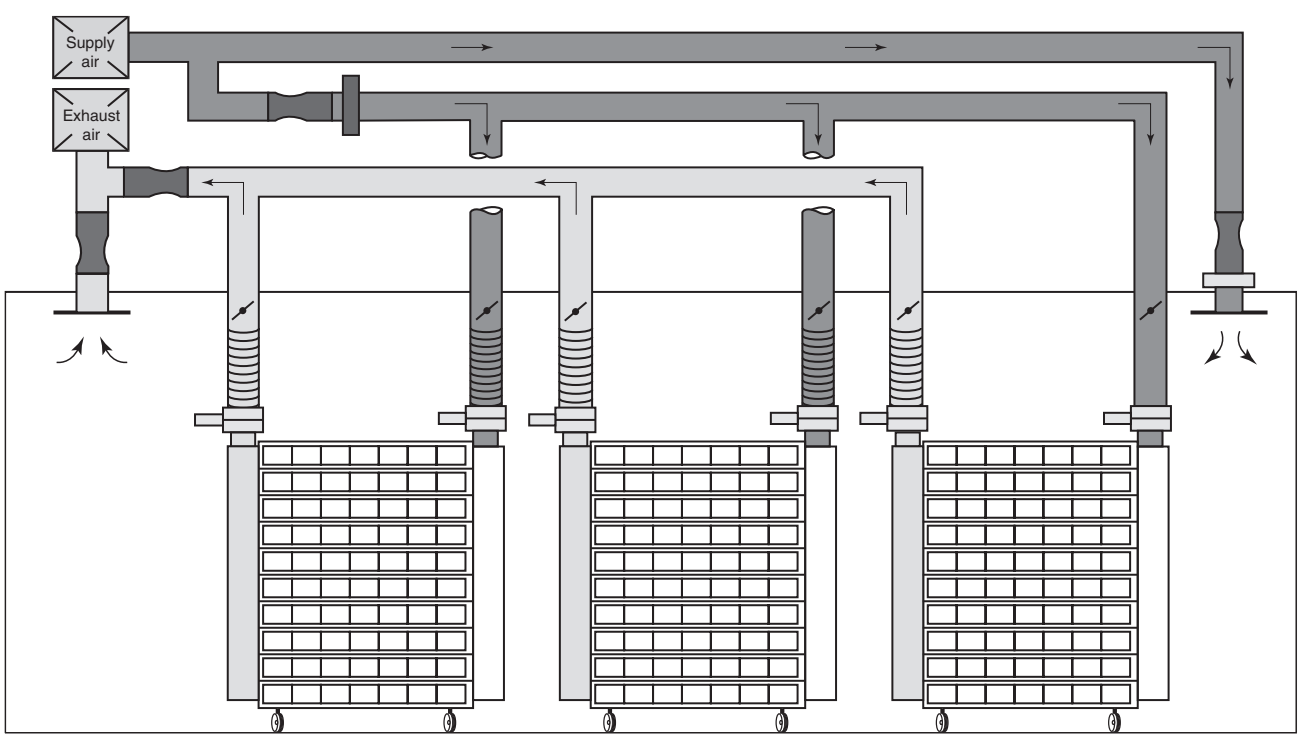

Fig. 34-11 Option 5: supply – building supply system; exhaust – hard-ducted to building exhaust. Airflow to and from each rack is controlled with a combination of an automatic pressure-independent valve controlling flow to or from multiple racks in a room and a manual balancing damper to and from each rack.
Figure courtesy of Phoenix Controls Corporation.

like Option 5, except that instead of branching off of the FSS to each room with ventilated racks, there would be branches off of a dedicated air supply system. The dedicated system would consist of a completely separate air handler and supply ducts providing 100 percent fresh, HEPA-filtered air at a preset constant temperature (e.g., 72°F, 22.2°C) and RH to all ventilated racks in the facility. Exhaust air from the ventilated racks could be tied into the FES by methods previously described. **Note**: The primary advantages of this configuration as compared with the previously described configuration is that it eliminates the extra terminal reheats required in branches supplying air to the ventilated cages and eliminates having to HEPA filter all the air being delivered to the facility. Another advantage is its relative simplicity. The cost-effectiveness of this option would depend on many factors, the most important of which is the number of ventilated racks in the facility.

A considerable amount of dust is generated inside rodent cages. This may create concern regarding dust from ventilated cages entering the facility exhaust system when air is directed from the cages to the exhaust system without being filtered. Some ventilated cage designs include filtering the air from the cage at the cage level before it enters the rack plenum and facility exhaust system. Some routinely filter the air between the rack plenum and the facility exhaust system – an option that is possible with most ventilated cages (see Option 1 above). Another option is to filter the air in the exhaust ducts just before the air passes across the heat recovery coils. Some do not consider dust enough of a problem to require filtering.

With any configuration for coupling ventilated cage racks to the facility's HVAC system, the animal room requires ventilation (supply and exhaust) rates and control features as required for handling the heat load in the room macro-environment and for balancing ventilation.

Chapter 20 of this book provides further details regarding integrating ventilated caging with the animal room and the entire facility's ventilation system.

E. Room Ventilation Patterns and Computational Fluid Dynamics

Computational fluid dynamics, or CFD, is the use of highly complex mathematical models to predict air circulation patterns in a space. Factors such as air temperature, flow rates, heat generation in the space, types and locations of air inlets and outlets, and objects in the space, are considered in CFD models. It is a powerful design tool for predicting how effectively a particular ventilation system design will function to meet the desired room conditions. Until a few years ago, it was widely accepted that the most effective animal room ventilation pattern is to supply air at the ceiling and exhaust it near the floor; however, there have been suggestions that other options are more cost-effective (Neil and Larson, 1982). Data from recently published CFD studies also give cause to reconsider this and other possible dogmas regarding animal facility HVAC systems (Hughes and Reynolds, 1994; Reynolds, 1994; Hughes *et al*., 1996; Curry *et al*., 1998; Memarzadeh, 1999; Jackson and Rehg, 2001). One CFD study suggests that a more efficient way to ventilate an animal room, in terms of removing airborne contaminants (heat, gases and particulates), is to supply and exhaust air at the ceiling in all four corners or, better yet, directly above each cage rack (Hughes *et al*., 1996). CFD data from the same publication suggest that an even more efficient configuration is to supply and exhaust room air from a soffit mounted in the center of the ceiling extending the full length of the long axis of the room. In this CFD model, supply air is directed from radial diffusers in the bottom of the soffit toward the floor. Exhaust inlets located along both sides of the soffit capture the air as it curls from the floor, up the wall parallel with the soffit, across the ceiling and into the soffit, where it is removed from the room. A full-scale test model of an animal room fitted with this type of soffit is reported to have performed better than predicted by the model (Hughes *et al*., 1996). In contrast to the CFD studies just cited, CFD studies conducted by the NIH Division of Engineering Services suggest that low returns are superior to ceiling returns (Memarzadeh, 1999). High returns in each corner or the soffit configurations are tempting options in that these are less costly to construct than low returns, and do not consume floor space. The very important question regarding "ideal" or "minimal effective" ventilation rates has been addressed (Hughes *et al*., 1996; Memarzadeh, 1999), but the answers are complex at best and the definitive answer, if there is one, has yet to be determined. A detailed description of CFD is provided in Chapter 35 of this book.

In rooms with open cage housing, airflow should not exceed 0.82 ft/s (0.25 m/s) at 5.9 ft (1.8 m) from the floor (NIH, 2003). In rooms with ventilated caging, the location of the room exhaust grill is less of a concern and is typically placed at one location in the ceiling at the opposite end of the room from the supply register.

IV. TEMPERATURE AND RELATIVE HUMIDITY (RH) CONTROL

A. Temperature

Temperature is one of the most critical environmental parameters to be controlled. Each animal room requires individual temperature control to adjust for the wide variability in heat loads due to species differences and/or animal density. The standard design temperature range for animal rooms is 65–85°F (18–29°C). A narrower range may be acceptable for facilities designed for a single purpose, such as rodent production. Room temperatures as low as 65°F (18°C) are desirable

for some commonly used species like rabbits, but occasions for room temperatures over 80°F (26.6°C) are rare, and usually involve the maintenance of relatively exotic species. Most critical is the ability to maintain a steady-state temperature in the animal room. The temperature control system should, at a maximum, be capable of maintaining temperature ±2°F (±1°C) around any set point selected from the designed temperature range (ILAR, 1996). Since rodents have minimal capacity to thermo regulate, relatively small excursions in environmental temperature can confound experimental results and moderate excursions can result in morbidity and mortality (Lipman and Perkins, 2002; Faith and Hessler, 2006).

B. Relative Humidity

Controlling relative humidity (RH) is of equal importance to controlling temperature control, but the degree of acceptable variability is much wider. The generally accepted range for RH control is between 30 and 70 percent. Usually RH can be controlled within this range without zone or room trim humidifiers. In fact, it is desirable to produce most or all humidification in the air handling unit (AHU) and avoid adding local trim humidifiers, which typically require considerable maintenance. Given the initial cost and maintenance issues, individual room trim humidifiers are rarely cost-effective. Zonal control may be desirable in some situations – for example, rooms likely to house only animals using dry bedding/litter systems could be zoned separately from those likely to house animals using large amounts of water for daily sanitation, such as dog and non-human primate rooms. As noted previously, ammonia production in rodent cages is directly related to the room RH (Hasenau *et al*., 1993; Memarzadeh, 1999). From this point of view, maintaining RH in the range of 30–50 percent would be highly desirable. Because low humidity can dehydrate young animals, especially newborn rodents, it is important to avoid RH below 30 percent. In cold climates this requires extensive humidification, and even in many warmer, moist climates some degree of humidification is required in cool weather.

C. Control Strategy

A typical strategy designed to control both temperature and RH is to deliver air conditioned by the air handlers to a temperature ranging from 52–55°F (11–12.8°C) and a RH exceeding 80 percent to hot water terminal reheats located in the supply air ducts to each animal room, where the air is warmed to a temperature controlled from a temperature sensor located in a common room exhaust air duct or in the room itself. The hot water terminal reheat coils should be controlled with variable solenoid valves that default in the *closed position*. The closed position is emphasized because it is critical; when valves that default in the open position fail, the animal room may over heat and kill the animals therein. Room temperatures as low as 85°F (29.5°C) can be fatal for some animals not adapted to warm temperatures, such as mice, rats and rabbits. A control sequence to shut down the air supply to the room or ventilated racks is recommended for situations when room temperatures exceed a critical value, typically near 80°F, to avoid rodent fatalities from heat exhaustion. Steam reheats should be avoided because the high temperature results in unacceptably wide fluctuations in the temperature of the room supply air and, potentially, the room.

V. CLEAN STEAM

Clean steam is recommended for humidification and autoclaves in order to avoid the potential confounding effects of chemical additives routinely used in steam boilers. Boiler additives are generally considered safe, without any known health effects, at the levels present in air humidified with boiler steam. However, the extent to which the chemicals might alter the research animal's biological response to an experimental variable is impractical to document for the wide array of animal models that may be used in a facility. In addition, the seasonal variation in the level of chemical additives in the air, being present in relatively large quantities in the winter and absent in the summer, is in itself an unnecessary environmental variable. For these reasons, chemically treated boiler steam is best avoided for humidification. For the same reasons, clean steam is also recommended for autoclaves that will be used for autoclaving animal husbandry equipment, such as cages and supplies like feed and bedding. Clean steam generated from house water is acceptable; however, generating it from distilled or reverse osmosis water is the best from a generator maintenance perspective.

VI. REDUNDANCY

The objective is to assure uniform maintenance of the research animal's environment without significant interruptions for repairs or routine maintenance of the HVAC system. This requires designing redundancy into critical HVAC system components, such as air handlers, exhaust fans, hot and cold water pumps, chillers, hot water heaters, other heat sources, and building automation systems (BASs). There are many options for providing redundancy for air handlers and exhaust fans. Examples are two parallel units, each capable of supplying 100 percent of design requirements (2 N); three parallel units, each with capacity for 50 percent of design requirements (N = 2 + 1); or four parallel units, each with capacity for 25 percent of the design requirements (N = 3 + 1). Other options include cross-connecting with other lower-priority sources to access available chilled water or steam. Having spare parts readily available for quick replacement is a less desirable

option, and only applies when exchanges can be made quickly (i.e., in less than 1 hour). When a central energy plant is used as a source of chilled water and/or steam, the availability of redundancy and emergency power for that source must be evaluated carefully. If an uninterrupted supply from the central plant cannot be assured, then dedicated chillers and boilers must be available to back up the central system. The importance of air system redundancy for biocontainment laboratories is much higher.

VII. CONTROL SYSTEMS, ENVIRONMENTAL MONITORING AND ENVIRONMENTAL ALERTS/ALARMS

A. Control

Reliably controlling an animal's environment is paramount. As a result, high-quality control components are essential. Control components must maintain accuracy in airstreams containing dust; operate accurately in crowded, complex and often short runs; provide stability and, in some instances, flexibility without the need for rebalancing or recalibration; and require minimum preventive maintenance. Integrating the HVAC control system with a building management system (BMS) to manage environmental controls in modern animal facilities offers many benefits not provided by standalone systems. In addition to facilitating control and monitoring of the complex HVAC system, an integrated system can be used for controlling many other aspects of the facility's environment, including animal room light cycles.

B. Environmental Monitoring

There is an ongoing debate concerning the use of the BMS exclusively for monitoring versus providing a totally independent vivarium monitoring system. While the BMS certainly monitors all environmental parameters of concern and much more, and has a good record of reliability, the mechanical and electrical components, including sensors that provide feedback to the control components, occasionally do fail. Clearly, the safest approach is to employ an independent monitoring system so that discrepancies between the control system and the monitoring system can be investigated and the problems corrected. If the problem is with the monitoring system, no harm has been done; if the problem is with the control system, disaster may have been avoided. In addition, an independent environmental monitoring system managed by the animal facility staff allows the animal facility management team to share in the important responsibility of assuring the stability and safety of the animals' environment.

Environmental parameters to be routinely monitored in animal rooms and animal procedure rooms include, at a minimum, lights (with light sensors in the room – not merely a signal sent from the BMS to turn the lights on or off), temperature, relative humidity and relative air pressure (positive or negative to corridor). It is also desirable to monitor airflows to and from animal room; however, it may not be cost-effective to duplicate airflow monitors required for the control system, since significant variations in airflow will be reflected either in room temperature and or relative air pressure. If ventilated cages are used, it is desirable to monitor the temperature of the exhaust air from the ventilated racks to detect single rack ventilation failures.

C. Environmental Alarms

Regarding the reporting of environmental parameters, there are innumerable combinations of daily, weekly, monthly and annual reports that may be required to document environmental conditions to accommodate management needs and standard operating procedure (SOP) requirements. Monitoring systems should be flexible enough to accommodate such needs. This section focuses only on reporting environmental alerts/alarms when environmental conditions range outside of preset ranges. There is no established terminology for various types of environmental warnings. The "Yellow Alert" (or Warning) and "Red Alarm" terminology discussed in this section is provided only to make the point that two levels are desirable. These are defined in terms of the level of response expected for each.

The purpose of Yellow Alerts is to detect a problem and correct it before the parameter being monitored reaches a point that requires immediate attention. These alerts are not considered an emergency, and do not require an immediate response during off hours. Physical plant maintenance should respond to these alerts at the first opportunity during regular work hours. A Red Alarm is considered an emergency that requires an immediate response by the physical plant if animals are housed in the room, and possibly by the animal-care staff if the problem cannot be corrected before the animals' well-being is jeopardized.

What to consider a Yellow Alert or a Red Alarm is a judgment call. The following is food for thought: relative humidity values outside of preset parameters (30–70 percent) need only be reported as a Yellow Alert. If airflows to and from a critical area, such as rooms and corridors inside a biocontainment area, are being monitored, the offset between supply and exhaust could be monitored and if it decreases to half its design value, this could be reported as a Yellow Alert; however, if the offset nears zero or actually reverses, this could be considered a Red Alarm. The same could apply if the relative air pressure is monitored in terms of actual pressure. If only relative air pressure is monitored as positive or negative, it may be considered a Red Alarm if a relative air pressure reverses from negative to positive at selected monitoring points. Lights failing to turn on or off may also be considered a Red Alert. Animal room

temperatures greater than ±2°F (±1.1°C) around the set point may be considered a Yellow Alert, but a temperature greater than ±6°F (±3.3°C) around the set point may be considered a Red Alarm. Having dual levels for reporting out-of-range environmental parameters eliminates the middle-of-the-night calls for non-critical reasons, such as high humidity, while still providing notice that the system is not functioning to its capabilities. Dual reporting levels also add more credibility to serious life-threatening conditions, such as high temperature, or conditions that jeopardize the research program, such as the lights failing to turn off.

VIII. NOISE CONSIDERATIONS

From a design perspective, the goal for animal housing and study areas should be for ambient noise to be kept below 55 dB within the frequency range of 10–100 kHz. The higher frequencies are a special concern when housing rodents, since they can hear at frequencies well above those people can hear (see Chapter 7). The primary source of ambient noise is the HVAC system. Air ducts should be sized and diffusers chosen to maintain noise levels in the room below 55 dB. Large ventilated rack fan/filter units supplying HEPA filtered air to multiple racks may require sound attenuation in the air duct between the fan/filter unit and the flexible duct to the rack. It is important to consider that multiple noise sources of equal value (e.g., 55 dB) add logarithmically – in other words, two 55-dB ventilated rack fans in the same room will generate an additional 3-dB of noise, giving a total of 58 dB. A total of four 55-dB fans would generate a total source of 61 dB.

IX. MAINTENANCE CONSIDERATIONS

Ideally, maintenance personnel should be able to fully service the animal facility's HVAC system without entering the animal facility. This is best accomplished by installing an interstitial space above the animal facility (see Chapter 13). If an interstitial space cannot be provided, then these components should be located above the corridor ceilings to eliminate the need for maintenance personnel to enter any rooms in the facility, especially animal rooms and animal procedure rooms. If the corridor ceilings are solid, strategically located access panels will be required to access critical HVAC components in space above the ceiling.

X. ENERGY CONSERVATION

Because of the high fresh-air exchange rates required in animal facilities, energy recovery systems may prove to be cost-effective, depending on local climatic conditions. Energy recovery systems must be limited to the types that preclude contaminating incoming air with outgoing air, such as runaround coils. These systems require glycol in colder climates to prevent freezing liquids inside the coils.

Another method of conserving energy is to recirculate a portion of the air in the animal facility. This requires cleansing recycled air of gaseous and particulate contaminants using combinations of HEPA filters and absorbents, such as alumina pellets impregnated with potassium permanganate or scrubbers. Such systems have not been widely used because of intensive maintenance requirements and the potential for cross-contamination in the event of a malfunction; however, newer technologies may enhance their desirability. Another energy-saving candidate may be VAV ventilation control systems. These provide only the amount of conditioned air required to maintain preset environmental conditions. For more information about using VAV to ventilate areas of the animal facility with widely variable heat loads, see the "Ventilation" section of this chapter.

XI. EMERGENCY POWER

To achieve the objective of controlling the animal's environment without interruption, emergency power capacity must be designed to maintain animal room lighting, animal room power outlets required by ventilated racks, and the entire HVAC system, including chillers and boilers. Other equipment requiring emergency power includes biosafety cabinets, refrigerators and freezers, and surgery room lights and power outlets.

XII. COMMISSIONING

Commissioning is a quality control process used to document and verify that the owner's project requirements are met for the facility. This process focuses primarily on the mechanical, electrical and plumbing systems, but also requires attention to the construction of the facility, including room tightness, finishes and door hardware, that will affect airflow direction and differential pressures. Commissioning also focuses on the BAS and sequences to verify stability and airflow control, pressurization, temperature and RH. Other systems for which verification is important are cage-wash areas, autoclaves, ventilated cage rack connections to building systems, lighting controls, fire alarm system interfaces and many specialty systems. Commissioning is required for biocontainment facilities Level 3 and higher (BSL3 and 4). The final product from the commissioning process is a recommendation from the commissioning authority for the owner to accept the facility to use for its intended purpose.

XIII. SUMMARY

The checklist below summarizes the key features of an HVAC system for a research animal facility. It is written as though it were part of a design program for a given facility; however, it is provided here only to stimulate the decision-making process for planning an animal facility. It is not meant to imply that all facilities will require all the features described in this checklist, or that the specific details listed (e.g., 95 percent efficient pleated filters) are intended as engineering standards whereby every animal facility should be designed. As noted above, there are ranges in the performance standards for animal facilities, and many more options for designing HVAC systems to meet those performance standards than are described above. As long as the focus is on achieving the objective of effectively controlling the research animals' environment within accepted performance standards, the project should be a success.

1. *Air quality*
   - Supply air – 100 percent fresh outside make-up air passed through 95 percent efficient pleated filters.
   - Exhaust air – ejected 80+ feet into the air with a plume exhaust system to prevent the mixing of exhaust air with intake air.
   - ABSL3 exhaust air – bag-in/bag-out HEPA filters, with automatic redundancy.
2. *Ventilation*
   - Constant volume will be used.
   - Ventilation rates are calculated to remove excessive moisture and heat, along with gaseous contaminants.
   - Animal and procedures rooms will have a minimum ventilation rate equal to that required by the ventilated racks and one exhaust canopy for a 6-foot Class II, Type A2 biosafety cabinet (previously called Class II, Type A/B3).
   - Stainless-steel canopy exhaust hoods will be placed above the load and unload doors of autoclaves and the tunnel and rack washers.
   - A cage sanitation area exhaust air system – a dedicated exhaust fan and welded stainless-steel ducts pitched to drain off condensed moisture into the sanitary sewerage system or back into the cage-washer – will be used.
   - The interior of the tunnel washer and rack washer will be hard ducted to the cage-sanitation area exhaust system.
   - The necropsy room will have downdraft necropsy tables and fume hoods through which much, if not all, of the room air will be exhausted. A dedicated exhaust air valve would preferably serve this device.
3. *Air balancing*
   - Relative room and area air pressures will be noted with arrows on schematic drawings once the drawings are completed.
   - Ventilation ducts and outlets, sized to avoid excessive noise and the rooms, will be balanced to avoid excessive pressure drops across the room door that result in whistling.
   - All penetrations of the envelope, other than the room door, should be sealed airtight to facilitate proper air balancing, as well as to avoid whistling.
   - The digital control system should be designed to automatically change relative air pressures in animal and procedure rooms from the keyboard.
4. *Coupling ventilated racks to the HVAC system*
   - Each animal room will have a prefabricated air filter module designed specially to supply HEPA filtered air to all of the ventilated cages in the room. It will be located in the interstitial space above the room, draw air from the room, filter the air and deliver it to the supply air side of each ventilated rack in the same room.
   - The exhaust side of each rack will be hard-ducted to the building's exhaust system. Fittings, two for each rack, will be installed at appropriate locations in the ceiling for connecting, with flexible ducting, the supply and exhaust air ducts on the cage racks to the supply and exhaust air ducts above the ceiling.
   - Airflow to and from the racks will be balanced by a combination of pressure-independent airflow control valves and manual balancing dampers at each rack. Procedure rooms will be similarly equipped to accommodate ventilated racks.
5. *Temperature control*
   - Temperature will be controlled independently in each animal room and procedure room at no greater than ±2°F around any set point from 65°F to 85°F.
   - The supply air handlers fitted with steam coils and chilled water coils will temper incoming air to 55°F year round.
   - Terminal hot water reheat coils with modulating solenoid valves will heat the air supplied to each animal room and procedure room. The default position for the terminal reheat solenoid valves *must* be "CLOSED."
   - The degree of terminal reheating will be digitally controlled from temperature sensors in the exhaust air duct coming from the room.
6. *Humidity control*
   - Relative humidity (RH) will be maintained from 30 percent to 70 percent year round.
   - The goal is to deliver 52°F to 55°F air with a minimum RH of 80 percent to the facility year round. During warm humid periods, the natural dehumidification that occurs with chilling the incoming air to 55°F is sufficient to achieve this objective without humidification; however, humidification will be required much of the year.
   - Clean steam will be used for humidification.

7. *Control and environmental monitoring*
   - The HVAC control system will be integrated with the campus-wide BMS.
   - An environmental monitoring system independent of the BMS will monitor the following parameters in all animal rooms and animal procedure rooms: lights (with light sensors in the room), temperature, RH, and relative air pressure (positive or negative to corridor). The exhaust air temperature from all ventilated racks will also be monitored and alarmed. Reporting features will include two levels: alerts and alarms. Alerts will be issued in daily reports of values that, over the last 24 hours, were outside the normal capabilities of the HVAC system but below alarm values. Alarms will be reported immediately when values jeopardize the animals' health and well-being. Reports should be archived for the Association for Assessment and Accreditation of Laboratory Animal Care International (AAALAC) purposes.
8. *Energy recovery*
   - A runaround coil system will be used to temper incoming air with exhaust air.
9. *Redundancy*
   - An N + 1 scheme will be used to provide redundancy for air handlers and exhaust fans. Examples include two parallel units, each capable of supplying 100 percent of design requirements (2 N); three parallel units, each with capacity for 50 percent of design requirements (N = 2 + 1); and four parallel units, each with capacity for 33 percent of the design requirements (N = 3 + 1).
   - Two parallel exhaust fans will be provided for the cage sanitation area, each capable of exhausting 100% of the design requirements (2 N).
   - Redundant hot and chilled water pumps will be provided.
   - Redundancy for chilled water and steam will be provided by cross-linking the animal facility chiller and boiler with chillers and boilers for the building.
10. *Power*
    - An emergency power generator will be provided with capacity to maintain all HVAC systems in the animal facility as fully operational, including chillers.
11. *Noise*
    - Ambient noise in animal housing and study rooms should not exceed 55 dB within the frequency range of 10–100 kHz. The ventilation system requires careful consideration. Sound attenuation may be required where frequencies of 10–100 kHz may be encountered.
12. *Maintenance*
    - Routine maintenance of the animal facility's HVAC system must be possible without entering an animal room, preferably without entering the animal facility. An interstitial mechanical space is ideal. If an interstitial space cannot be installed, all mechanical components requiring routine maintenance must be located above the corridor ceilings.
13. *Energy conservation*
    - Energy recovery systems that preclude cross-contamination of incoming air with outgoing air should be evaluated to determine whether these are cost-effective.
14. *Emergency power*
    - The animal facility's environmental control systems should be fully covered by emergency power, including chillers and boilers.

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Chapter 35

Using Computational Fluid Dynamics (CFD) in Laboratory Animal Facilities

Scott D. Reynolds

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From the early 1990s through the first decade of the new millennium, architects and engineers began using newly available design tools to create cutting-edge, state-of-the-art animal facilities. These tools include three-dimensional computer visualization, advanced CAD and comprehensive commissioning software, among others. Another design aid is a numerical airflow modeling technique that has been in existence for well over a century but has only become useful since the 1970s; and that is only because of explosive advances in computers between the 1970s and 1990s. This technique is known as computational fluid dynamics (CFD). CFD is the computer embodiment of the laws of physics that govern the coupled parameters of air movement, energy transfer, gas diffusion, kinetic reactions and particulate motion. This software has become an

increasingly important aspect of facility design because of its unique capability to predict and visualize how ventilation air in a facility will behave. Every important feature of flow may be modeled, including: flow patterns, pressures, temperature stratification, odor permeation, airborne chemical contamination (e.g., ammonia, indole, skatole, cleaners and anesthesia gases), humidity prediction and general indoor air quality (IAQ). Additionally, CFD can benefit the building design by identifying opportunities for improvements to energy efficiency and can be used for exterior wind wake studies, both of which are worth valuable points towards a LEED certification from the US Green Building Council (US Green Building Council, 2005).

When CFD made its debut in the 1960s, only government agencies such as NASA and certain academic institutions could capably use the software. During the early years of the 1960s and 1970s, the results of CFD were typically printed on reams of paper and were only useful to people skilled in the field (Biswas, 2004). Today, most CFD software packages include spectacular intuitive graphics capabilities that can display the data in a plethora of output types. Detailed below are some of the available visualization capabilities of typical CFD software packages, followed by specific applications of how the technique may be employed in the lab animal arena.

I. VISUALIZATION OUTPUT

1. *Velocity vectors* (Figure 35-1). This type of plot shows length- and color-coded arrows plotted on a plane cut through a room or space (also known as the domain) representing both the speed and direction of flow. Some engineers choose to color the vectors by variables other than speed, such as chemical concentration or temperature.
2. *Contours* (Figure 35-2). This visualization type includes lines or filled areas depicting regions of a constant parameter such as concentration, temperature, pressure, etc. A common example of this method outside of the engineering field is a weather map showing temperatures across the country or in a region.
3. *Path lines* (Figure 35-3). The path line feature is a very useful technique to show flow in three dimensions throughout a room, building or a building's exterior. This visualization technique shows 3-D trails left behind the progression of imaginary, mass-less particles dropped into the analysis space. The tracks precisely follow the momentum of the air currents and are not affected by gravity. These paths can be colorized by velocity, temperature, dwell time or any variety of other variables.
4. *Particle tracks*. This visualization type is very similar to path lines except that the imaginary particles actually have a defined size (or distribution of sizes), density and generation rate. The particles also have defined properties of impact, such as bouncing behavior or particles that stick

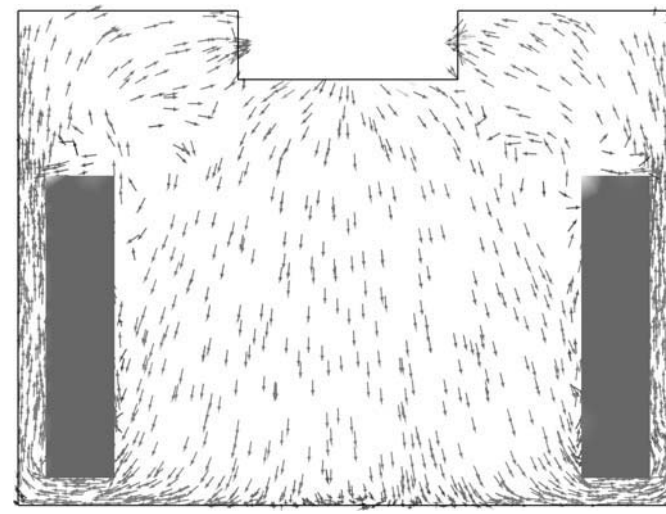

Fig. 35-1 Velocity vectors on a plane cut through a rodent holding room.

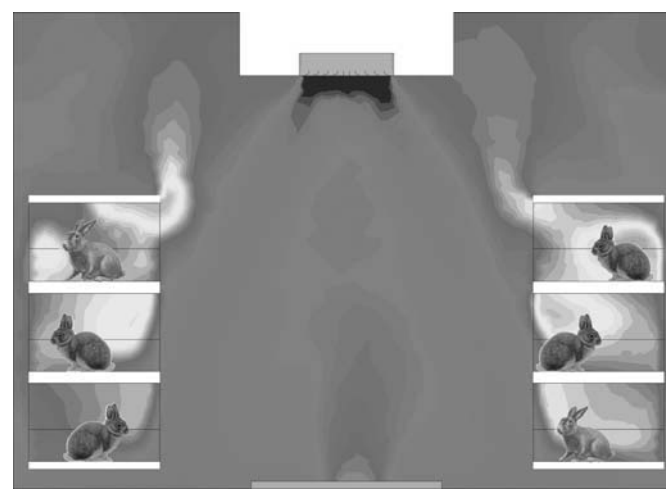

Fig. 35-2 Temperature contours on a plane cut through a rabbit holding room.

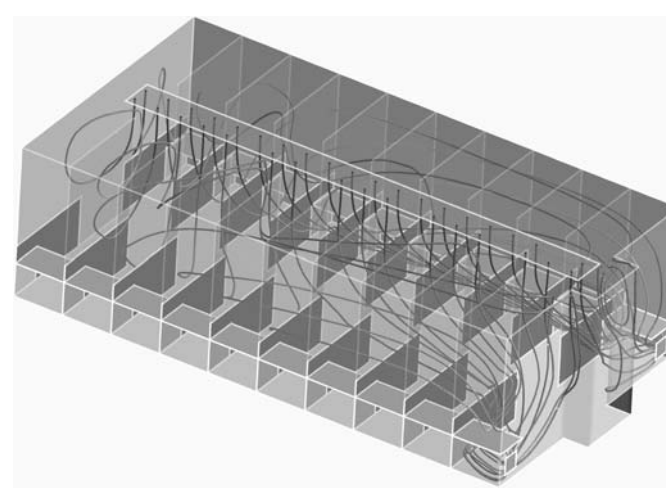

Fig. 35-3 Path lines migrating through a kennel.

when they collide with obstructions. Path lines and particle tracks can also differ in appearance. Particle tracks will tend to show a drop toward the floor by the laws of projectile motion for heavier, larger particles, but may remain indefinitely suspended for very small particulates; the latter is known as Brownian motion. Particle types can include dander from animals, fomites from cages, room dust, dirt, feathers, fur and powdered medications.

5. *Isosurfaces* (Figure 35-4). When it is desirable to view contours in three dimensions, isosurfaces are useful. An isosurface is equivalent to a single contour level except that it forms a three-dimensional cloud. In other words, an isosurface is the surface of a cloud that exhibits a single value of some variable (e.g., 2 ppm of isoflurane). This technique reveals the permeation of a chemical, for instance, into the three-dimensional space. It is intuitive, since it looks like a cloud of smoke and is easy to interpret even to those not experienced in the field. The isosurface may also be embellished such that the cloud appears to be translucent or partly transparent.
6. *Clipped isosurfaces* (Figure 35-5). If multiple isosurfaces are displayed simultaneously and a portion of the clouds is clipped away to reveal their interior, this is generally referred to as clipped isosurfaces. The resulting plot looks somewhat like a sliced onion where the multiple concentric layers are exposed. Each layer would represent a different value of a parameter, such as concentration, for instance.
7. *Profiles* (Figure 35-6). This visualization technique is rarely used, although its appearance is usually very attractive. Profiles consist of a contour plot on a particular plane whose surface is accentuated with raised areas proportional to magnitude. A common example of this type of output would be a relief map where "valleys" are blue in color and situated close to the contour base plane, whereas mountains are red in color and raised up away from the base plane.
8. *Animations*. Adding some degree of motion to any of the above output types is known as animation. This type of output is usually fascinating to the casual observer (and even the non-casual observer), but rarely adds substantially to the understanding of the analysis. There are times when animations are useful. For instance, if a transient study is performed to calculate the permeation of gases into a room or a time-dependent event occurs that changes room temperature, animations may be warranted and useful. Additionally, information on the migration of particulates into a room space as a result of an event such as a powder-vial spill may be better described by animations.

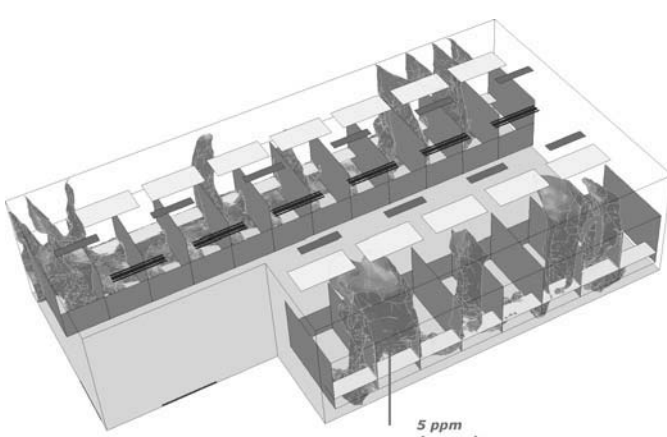

Fig. 35-4 Isosurface of 5 ppm of ammonia in a kennel.

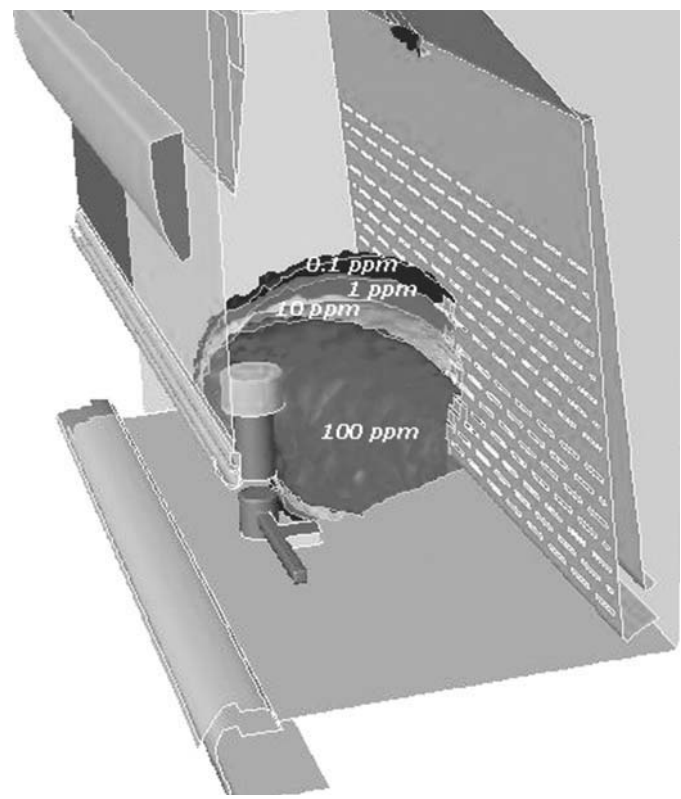

Fig. 35-5 Clipped isosurfaces of 0.1, 1, 10 and 100 ppm of SF6 in a fume hood.

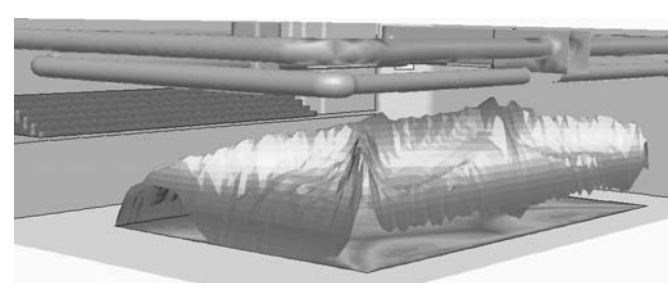

Fig. 35-6 Profiles of chloramines in a natatorium above a swimming pool.

II. HOW IS CFD USED IN THE DESIGN OF AN ANIMAL FACILITY?

Ideally, CFD should be used as early as possible, and the results shared with the design professionals, owner, facility managers and veterinarians (the design team). Typically, the design engineers will propose a ventilation scheme based on current design guidelines that they believe is optimal for the application at hand, and then present the concept to the design team. After comparison and review of both the ventilation design and the CFD analysis results, the team will often make suggestions to optimize the design further. This usually includes changes to the supplies, returns and exhausts, followed by another CFD analysis of the new concept. Alternately, the design engineers will propose several equivalent designs to be evaluated with CFD and, once modeled, will select one or more scenarios to present to the team. Typically, a list of target parameters must be addressed, such as room turbulence, temperature stratification, particulate loading or gaseous build-up. Also, there are usually several significant challenges to overcome related to the differences in requirements for humans versus the housed animals. For example, a facility owner may wish to use ventilated racks where the rack exhausts are hard-connected to the building exhaust system (Bilecki, 2002; Phoenix Controls, 2002). Because virtually all the humidity, ammonia and particulates are expelled into the building exhaust, many of the normal problems associated with these loads are circumvented. Although it may seem that most of the heat generated from this rack-exhaust arrangement will also be expelled from the room through the same route, in reality only about a third is extracted while the balance is dissipated in the room by convection and radiation – so the HVAC designer must accommodate for two-thirds of the animal heat load and all of the loads from blowers (if present) when sizing up the HVAC for that particular holding room. If this point is neglected, it then becomes a very compelling argument, for energy and first-cost reasons, to lower the ventilation rate in the room to four or five air changes per hour (ACH). While the animals may still be safe from a thermal standpoint, the low room ventilation rate may not be high enough to handle any additional heat loads such as lighting, biosafety cabinet loads or stale, lingering air. This, of course, could end up being very uncomfortable for employees because of stagnant air and elevated temperatures. Additionally, disastrous results can occur if very low ventilation rates are initially selected and the function of the room changes over time. For example, a room initially populated with 6 ventilated racks may be changed over time to accommodate 10 racks with an additional change hood or a vented biosafety hood. The exhausting of air through the racks could then easily exceed the supply rate to the room, thereby causing a case where the room becomes very negatively pressurized. When the room becomes excessively negative, air is necessarily drawn from the corridor or adjoining rooms, resulting in a potentially severe cross-contamination problem. Further, the air handlers for the building supply will likely be undersized and incapable of accommodating the changes to the rooms. These types of problems may be headed off by using CFD to examine various future room-usage scenarios. These may include disconnected racks discharging to the room, the effects of portable HEPA filters for particulate control, and the effects of temporary or permanent static caging generating both odors and allergens into the room.

III. THE APPLICABILITY OF CFD

CFD is not limited to studies of only rooms. It can be used to evaluate the latest individually ventilated cages, isolation cubicles (Curry *et al*., 1998), surgery suites, cage-wash areas, euthanasia chambers, exterior exhaust stack dispersion and a litany of other applications. As examples, Figure 35-7 shows a CFD analysis of a typical individually ventilated cage, whereas Figure 35-8 shows the dispersion of chemicals from the roof stacks of a building.

CFD can also be used to evaluate the effects of room ventilation on individual open caging systems (Riskowski and Memarzaden, 2000; Figure 35-9). For example, it may be

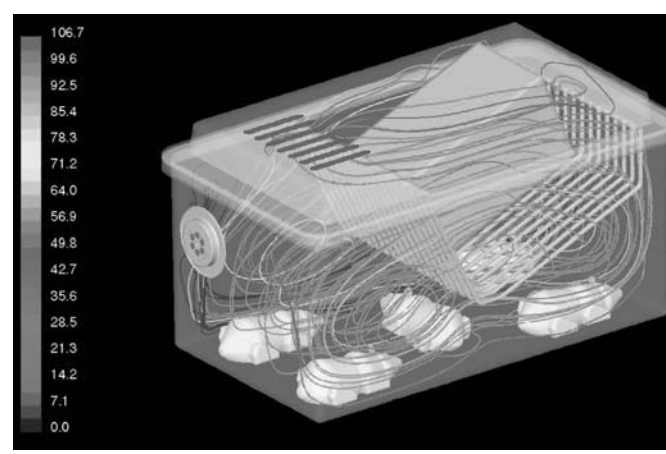

Fig. 35-7 Path lines in a typical individually ventilated mouse cage.

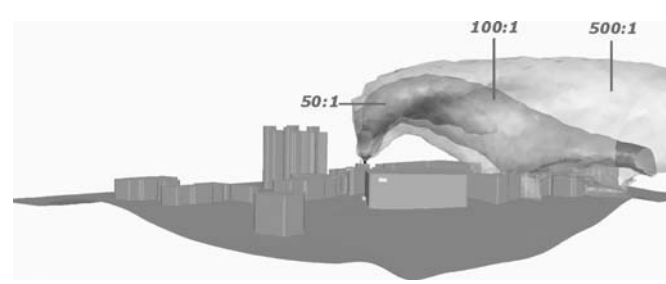

Fig. 35-8 Dilution ratio isosurfaces from a lab roof top stack.

desirable to direct fresh room-supply air into open caging in an effort to keep the bedding dry, thereby limiting ammonia generation and continuously supplying fresh air to the animals. On the other hand, direct flow of cool dry air into open caging could have implications for wound healing, thermal comfort, or drying of eyes in the case of ocular studies.

The design team must use the results of the CFD studies to judge whether the specific mechanical aspects of the ventilation schemes will have any adverse physiological or other detrimental impacts on animals or humans.

IV. USING CFD TO FIND OPTIMAL CONDITIONS

Generally, design professionals are challenged with three often competing tasks when planning a new building:

1. Animal comfort and health
2. Human comfort and health
3. Energy efficiency.

CFD can be used to effectively find an optimal operating point that addresses most or all of these tasks simultaneously.

A. Animal Comfort and Health

There is an abundance of guidelines available for the design of optimal environments for animals in typical lab animal facilities (Ruys, 1991; ILAR, 1996, 2004; NIH, 1999; ASHRAE, 2003; CDC/NIH, 2007). Most of these guidelines recommend the use of CFD as a method to more fully understand the ventilation of a facility and help thwart any adverse effects on their animal inhabitants. Computational fluid dynamics is not limited to just the facility where animals are kept; it can also be used for their housing systems.

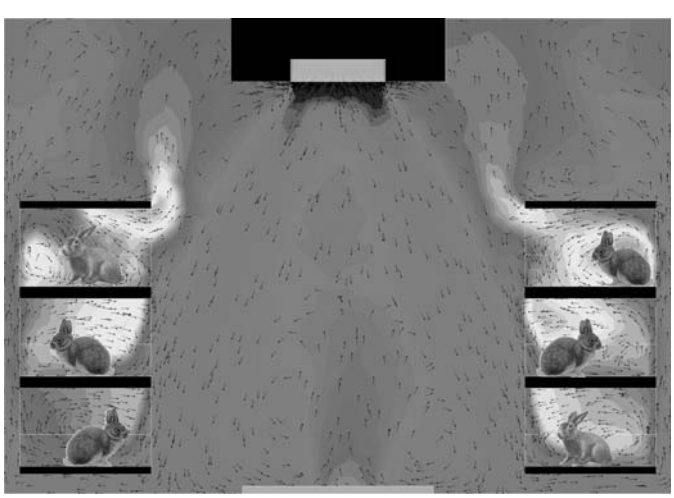

Fig. 35-9 Velocity vector and temperature contour plot of a rabbit holding room.

CFD has been successfully used to model the microenvironment of cages. Both ventilated and non-ventilated styles have been examined, from the top-line isolator, full-barrier cages down to the older styles of wire-mesh cages (Riskowski and Memarzadeh, 2000). Using CFD, the analyst may determine the relative concentrations of ammonia between styles of cages, aiding in the selection of the proper cages for the owner's applications. Additionally, the analysis is not limited to ammonia concentrations; it can also shed light on internal cage temperatures, humidity levels, the velocity of air passing through the cage, and any confounding stratifications (temperature, particulates or gases) that may develop as a function of cage design. Further, the animals' body shapes and heat generation can be accurately modeled using CFD.

Moreover, analyses can be applied to full racks of cages to evaluate inherent temperature differentials between, for instance, the top tier of cages and the bottom tier. It is often very important to maintain a constant temperature at all levels in the rack to ensure constant physiological and metabolic function of the animals throughout. Sometimes rack studies become essential to guarantee that temperatures in the top tiers do not exceed the critical limits of survivability for the animals (ILAR, 2004: 111).

B. Human Comfort and Health

The aspects that are important to the comfort and health of humans relate to the overall indoor air quality (IAQ) in the areas housing animals. The parameters usually affecting IAQ include temperature, humidity, odors, allergens, other airborne particulates, and chemical contamination. Usually, the optimal environment for humans is not the optimal environment for the animals. By their very nature, animals are usually the largest contributors to the degradation in IAQ for humans. For instance, many animals in a room provide a large energy source, thereby causing room temperatures to generally increase and stratify. Open caging can release large quantities of humidity, odors and allergens into the air, thereby making the air seem stale and "heavy." Inadequate ventilation can amplify the influence of the animals on the facility by not removing enough contaminates from the breathing zones of the humans.

CFD can aid the facility designers in planning for optimal placement of supply diffusers and exhausts. Through this ability, the best IAQ may be provided in areas occupied by humans while simultaneously providing an environment that is optimal for the animals. For example, this may entail suggestions for the best placement of racks, location of specially designed exhausts in close proximity to the animals, and the use of supply diffusers that may be radial in nature (Hughes and Reynolds, 1995, 1998; Morse *et al*., 1995; Hughes *et al*., 1996; Reynolds and Hughes, 1997; Curry *et al*., 1998; Jackson *et al*., 1999; Reynolds *et al*., 2003).

In some cases, the function of animal holding rooms may change. This can occur when the focus of animal studies changes and different species are introduced to the space. Commensurate with particular changes in species are potential changes in heat load, the potency of allergens, the strength of odors and the amount of humidity dumped into the area. CFD is frequently used to determine the effects of changing species and their rack styles. Of course, the changes could affect the preferred environment for both the animals and humans. Predicting ventilation for the potential future needs of the facility will allow the design team to provide for maximum flexibility over a long period of time.

C. Energy Efficiency

The last task for the design professionals is to navigate toward an energy-efficient mechanical system that is also flexible for future concerns and effective for IAQ concerns. Organizations such as the American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) have gone to great lengths to formulate guidelines for ventilation system design that can serve these purposes (ASHRAE, 2003). Unfortunately, the guidelines tend to be extremely generalized and overly conservative, not lending themselves to aggressive energy efficiency design. CFD on the other hand is application-specific, capable of modeling all of the important features for each area of a facility. Through this capability, CFD may be used to suggest very accurate placement of ventilation components and the quantity of air required to properly ventilate the area, and to describe both the minimum rate of operation and a maximum rate where the point of diminishing returns is exceeded. Ventilation criteria set forth by ASHRAE and the *Guide* suggest using a range of air changes per hour (ACH), usually 8–15 ACH. By specifying ventilation in these terms, the efficiency of the air delivery and extraction from the indoor space is not accounted for and is ignored altogether. In other words, the distribution of air is ignored and perfect mixing is assumed with the other techniques.

An example of a ventilation system that was designed to *exceed* ASHRAE guidelines but failed adequately to ventilate the room follows. A large animal holding room was designed with the supplies and exhausts located in close proximity to one another, high in the room. The holding area was said to have smelled so bad that "you could smell it from the parking lot" (S. Reynolds, personal communication, 1996). After applying CFD to the problem, it was quickly determined that fresh air was forming a short circuit between the supply and the exhaust, leaving the bulk of the room unventilated and stagnant. The results of the CFD analysis indicated that the supplies should be offset away from the exhausts, fresh air delivered down the center of the room, and the exhausts moved to symmetric low locations. The re-evaluation of the space showed excellent one-pass flow which has the highest likelihood of extracting contaminants and odors. The facility was renovated and, when put into operation, demonstrated excellent ventilation performance. The IAQ was improved for the humans and animals, and provided for an overall reduction in energy because of the increased efficiency in ventilation (Morse *et al*., 1995). Other success stories exist as well for novel one-pass ventilation designs. Some of these techniques actually increase usable floor space by reducing the space required for exhaust drops to floor level (Hughes and Reynolds, 1995; Hughes *et al*., 1996; Jackson *et al*., 1999).

V. USING CFD TO HELP WITH ACCREDITATION AND LEGAL ISSUES

AALAC accreditation and FDA regulations require that a certain air quality be maintained in any animal holding facility. By performing CFD analyses on the ventilation, it is proof of "due diligence" on the part of the design professionals and the building's owner. Additionally, if there is a future litigation claiming that the facility was not designed properly with respect to ventilation, or that there was some sort of chemical or allergen exposure, the owner can prove due diligence here as well. Additionally, the *Guide* recommends using CFD to optimize flow within animal holding rooms (ILAR, 1996).

VI. INTERPRETING THE RESULTS OF CFD AND PUTTING IT TO USE

In order to fully realize the benefits of CFD, the information from the analysis must be understood and interpreted. Additionally, it is very helpful for the benefactors to know what to look for in advance; they should be able to list their objectives for the study and have an idea of what performance is acceptable and what is not. The best ventilation scenario for typical animal holding rooms is one where:

- the room is uniform in temperature;
- supply air is delivered fresh at relatively low speeds everywhere;
- one-pass behavior from supply to exhaust is exhibited;
- exhausts are placed close to the sources of contamination; and
- the airflow demonstrates few, if any, vortices (swirls) or dead zones.

Of course, the ventilation solution must not be prohibitively expensive and it should represent something that can actually be constructed.

VII. INTERPRETING AIRFLOW

Certain types of CFD output are better than others for shedding light on the ventilation efficacy. The preferred methods to

show airflow are through velocity vectors on several strategically located slice planes, and path lines emanating from the supply diffusers and from the cages. These two techniques will allow the users to see where vortices are forming, any dead spots, and the locations of long-duration supply-to-exhaust paths. Both techniques will provide information on local airflow velocities, thereby indicating comfort and ventilation efficiency. Temperature contours can effectively show the minimum and maximum temperatures, along with potential stratification that may arise. Concentration contours are effective for quantifying ammonia (urine-based) and skatole/indole (feces-based) odors, carbon dioxide (respiration) and other chemicals such as isoflurane (anesthesia gas). The best designs do not necessarily keep all of the odors from entering the room, but rather keep the odors from reaching the human breathing zone.

There are instances when the flow from the supplies appears to be "squeezed" from rolling flow in the room. Many times, a typical pattern of flow will start at the supply diffusers, flow to the floor, bifurcate and flow toward the walls, then up the walls and, if enough momentum remains, flow back across the ceiling toward the supplies. It is the last step of the flow pattern that can interfere with the supplies by applying lateral momentum on both sides of the diffusers that is perpendicular to the entering flow. By "squeezing" the flow in this manner, the aisle and racks will not experience a uniform, slow source of fresh air; in fact, the possibility of large rolling vortices increases greatly. These vortices act to draw allergens and odors directly into the zone that humans are likely to occupy. Further, because the air is recycled in the area of the racks, the temperatures are likely to stratify from the bottoms of the racks to the tops. This situation usually occurs because the supply flow is too low and the exhausts are not strategically placed to achieve one-pass flow. The "squeezing" effect can be readily observed using velocity vectors and path lines.

Another situation to avoid is dead spots throughout the area being modeled. Dead spots show up as velocity vectors that are at (or very close to) zero velocity. Dead spots can cause a significant degradation in IAQ, are more likely to contain contaminated air (odors, allergens and pathogens) than moving air, and make the air in the area feel "heavy." In the ideal case, both the velocity vector and path-line plots should reveal air speeds of about 30–50 feet per minute (fpm) at all points in the area modeled. There should be no high-speed air ($>$120 fpm) either at the racks or in the aisle, and the path lines should take the shortest path out of the room while still passing by the sources of contamination.

VIII. INTERPRETING TEMPERATURE ISSUES

Temperature is another important consideration in animal holding facilities. Typically, animal heat load, biosafety cabinets, change stations, lighting and other equipment will have a propensity to increase the temperature of the room. Rooms and other areas that exhibit poor ventilation efficacy will tend to show cool and warm pockets of air throughout. It is relatively common to see temperature stratification in most rooms, as opposed to very pronounced stratification in areas that have poor ventilation. ASHRAE has developed guidelines to help engineers calculate both the quantity and temperature of supply air to carry away all of the heat and maintain a comfortable environment during all seasons of the year. What ASHRAE fails to consider, however, is the effectiveness of the ventilation; all rooms are considered to have the same distribution efficiency, and no attention is given to the placement of supplies or exhausts.

On a cage level, both the room and its cages should operate synergistically to prevent temperatures from exceeding about 86°F in the cages. The thermal-neutral zone for most rodents is between 82 and 86°F, but rapid changes in temperature from this range can be fatal to the animals, so great attention must be given to the maintenance of reasonable temperatures at all times (ILAR, 2004: 97, 111). Acceptable cage temperature ranges for group-housed rodents might be 75 $\pm$ 5°F, but would be even better at 73 $\pm$ 3°F for safety.

Temperature contours taken through the racks of cages can show both the internal cage temperatures from animal heat and the resulting room temperatures simultaneously.

IX. INTERPRETING CONTAMINATION GAS BEHAVIOR

Ammonia is one of the most common contaminants in an animal room, particularly for rodents housed in unventilated caging. The odor threshold, where the chemical is barely detectable to 50 percent of people, is around 5 parts per million (ppm), and the Permissible Exposure Limit (PEL) for ammonia is 25 ppm. Recent studies have shown, however, that, unlike humans, many animals are not affected by ammonia until concentration levels exceed several hundreds or even thousands of ppm. Although some studies show no significant effects of high ammonia concentrations on mice (ILAR, 2004), it is unknown whether long-term exposure at these levels will have any adverse health effects, but intuition would suggest that it does.

Concentration contours may be used to determine the range of gas permeation both at a cage level and throughout the room. A practical guideline would be to maintain gas concentrations at, or below 10 ppm. Of course, the lower the concentrations, the better the room will smell.

Another useful technique to gauge gaseous permeation into a room is by isosurface plots of gas concentration. Because isosurfaces are really three dimensional contours, the migration of the gas can be plotted in an isometric view and will appear as a cloud in space. This cloud will represent a specific

concentration of the gas, and therefore is helpful in showing where a threshold boundary may exist. So, for instance, if the cloud surface represents the maximum allowable concentration for a gas and it is completely clear of a room's aisle way, the environment is likely to be comfortable to the care-givers (at least from an odor standpoint).

In order to assess accurately the ammonia in a given room, the generation rate must first be determined. A few studies have shown that typical ventilated cages housing mice with a bedding age between 14 and 21 days will produce ammonia concentrations of about 21 ppm. Open-top cages with a bedding age of about 1 week will produce local concentrations in the order of 15 ppm (Reeb *et al*., 1998).

X. OTHER IAQ-RELATED ISSUES

The mean age of air in a room or facility can be calculated using CFD, and plotted using contours, isosurfaces or pathlines. Theoretically, the longer air lingers inside a building, the more opportunity there is to accumulate CO_2, allergens, pathogens, humidity, odors and heat. Thus, plots showing a relatively short mean air age will usually indicate "fresher air" while the longer ages will be reflective of "stale air." CFD also has the capability to evaluate air that has been lingering in the domain and then is recirculated, such as with change-hoods or biosafety cabinets. Both of these examples can effectively filter particulates, but gases or odors will remain just as potent after discharge as they were before entering these devices.

XI. CAUTIONARY NOTES

There have been some reports in the past where CFD did not meet the expectations of a facility owner. These problems, whether real or perceived, could have been avoided by following a few simple guidelines for selecting and using a CFD consultant.

1. Always use a consultant or corporate engineering staff whose predominate business is CFD. Avoid using inexpensive labor, such as graduate students or summer interns, or professors who have relatively little experience in the field. Avoid "dabblers" – firms that use CFD a few times per year but have not yet put any significant resources into their CFD services. Ask them how many studies they perform each year with CFD, and how often.
2. Always utilize a consultant with a strong knowledge of building systems. It is preferable to use an engineer who is well versed in HVAC and control system design, and who is also knowledgeable about animal housing systems, the various types of animals that may be used, and the idiosyncrasies involved with typical animal holding facilities.
3. Avoid modelers that use inferior CFD software or shareware. Use software that has a good reputation, has been in use for many years, and has been verified as accurate.
4. Work with the CFD consultant to make sure all of the inputs and other design details of their models are accurate. A model can be very precise in terms of its geometrical dimensions; however, if, for instance, the flow rates entering or leaving a room are incorrect, the output can also be incorrect. Make sure that the consultant has all the diffuser types and locations planned for the room(s); all the exhaust locations and sizes; the number, location and dimensions of all racks; the expected heat load or number of animals and the species involved; any of the mechanical or electrical heat loads; and any miscellaneous items that may contribute to the models' accuracy.
5. Be certain that the design team's expectations for the modeling effort are put in writing at the initiation of the project, and that all goals have been articulated to the consultant. This prevents surprises and misunderstandings later in the design and construction cycle.
6. The design team should insist on a final summary that is verbal, written (including electronic presentation) or both. Anything that is not understood by the design team should be questioned. If any opportunities for better ventilation, higher energy efficiency or greater comfort are revealed in the final phase, the team should consider exploring follow-on models that will confirm the performance.

XII. AFTER THE MODELING IS COMPLETE

The design team and construction personnel should *never* make "substitutions" to HVAC components that may be critical to effective ventilation after the models have been executed, unless the CFD consultant indicates that those replacements are beneficial in some way or neutral. There are documented cases (S. Reynolds, personal communication, 1998) where substitutions to modeled HVAC components were implemented after the CFD analyses were completed, resulting in dramatic consequences such as: failures of the ventilation system, very poor IAQ, energy inefficiency, a significant waste of capital resources or significant delays in construction.

If the modeled portions of the facility are not working as anticipated, the design team/facility owner should approach the CFD consultant in an effort to determine the cause of the problems. Usually, many of the issues are related to substitutions or balancing, but it doesn't hurt to revisit the models or the design.

Finally, the team should insist that the CFD consultant retains softcopies of the analyses for future use. If the functionality of the building should change in the future, the consultant may be able to use the existing files to more quickly evaluate the spaces involved.

XIII. SUMMARY

CFD can provide a very powerful tool to aid in the effective design of HVAC system performance in lab animal facilities. Combining all of the output types available through CFD, the design team should be able accurately to evaluate, predict and subsequently design the future ventilation performance of a facility. Three major goals are desired for the final design: human comfort, animal comfort and energy efficiency. A dynamic design team can, with the help of sophisticated CFD utilization, deliver all of these goals.

APPENDIX: CFD APPLICATION EXAMPLES

Below is a partial list of applications that has benefited from CFD analysis:

a. Cage-level modeling
   i. Wire mesh
   ii. Shoebox
   iii. Micro-isolators
   iv. Ventilated caging
   v. Fish tanks
   vi. Hybrid caging
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