CHAPTER 14

LABORATORIES

MODERN laboratories require regulated temperature, humidity, relative static pressure, air motion, air cleanliness, sound, and exhaust. This chapter addresses biological, chemical, animal, and physical laboratories. Within these generic categories, some laboratories have unique requirements. This chapter provides an overview of the HVAC characteristics and design criteria for laboratories, including a brief overview of architectural and utility concerns. This chapter does not cover pilot plants, which are essentially small manufacturing units.

The function of a laboratory is important in determining the appropriate HVAC system selection and design. Air-handling, hydronic, control, life safety, and heating and cooling systems must function as a unit and not as independent systems. HVAC systems must conform to applicable safety and environmental regulations.

Providing a safe environment for all personnel is a primary objective in the design of HVAC systems for laboratories. A vast amount of information is available, and HVAC engineers must study the subject thoroughly to understand all the factors that relate to proper and optimum design. This chapter serves only as an introduction to the topic of laboratory HVAC design. HVAC systems must integrate with architectural planning and design, electrical systems, structural systems, other utility systems, and the functional requirements of the laboratory. The HVAC engineer, then, is a member of a team that includes other facility designers, users, industrial hygienists, safety officers, operators, and maintenance staff. Decisions or recommendations by the HVAC engineer may significantly affect construction, operation, and maintenance costs.

Laboratories frequently use 100% outside air, which broadens the range of conditions to which the systems must respond. They seldom operate at maximum design conditions, so the HVAC engineer must pay particular attention to partial load operations that are continually changing due to variations in internal space loads, exhaust requirements, external conditions, and day-night variances. Most laboratories will be modified at some time. Consequently, the HVAC engineer must consider to what extent laboratory systems should be adaptable for other needs. Both economics and integration of the systems with the rest of the facility must be considered.

The preparation of this chapter is assigned to TC 9.10, Laboratory Systems.

LABORATORY TYPES

Laboratories can be divided into the following general types:

- **Biological laboratories** are those that contain biologically active materials or involve the chemical manipulation of these materials. This includes laboratories that support such disciplines as biochemistry, microbiology, cell biology, biotechnology, immunology, botany, pharmacology, and toxicology. Both chemical fume hoods and biological safety cabinets are commonly installed in biological laboratories.
- **Chemical laboratories** support both organic and inorganic synthesis and analytical functions. They may also include laboratories in the material and electronic sciences. Chemical laboratories commonly contain a number of fume hoods.
- **Animal laboratories** are areas for manipulation, surgical modification, and pharmacological observation of laboratory animals. They also include animal holding rooms, which are similar to laboratories in many of the performance requirements but have an additional subset of requirements.
- **Physical laboratories** are spaces associated with physics; they commonly incorporate lasers, optics, nuclear material, high- and low-temperature material, electronics, and analytical instruments.

Laboratory Resource Materials

The following are general or specific resource materials applicable to various types of laboratories.

- ACGIH. 2001. *Industrial Ventilation: A Manual of Recommended Practice*, 24th ed. American Conference of Governmental Industrial Hygienists, Cincinnati, OH.
- AIA. 2001 ed. Guidelines for Design and Construction of Hospital and Health Care Facilities. American Institute of Architects, Washington, D.C.
- AIHA. 1993. Laboratory Ventilation. ANSI/AIHA *Standard Z*9.5-93. American Industrial Hygiene Association, Fairfax, VA.
- BOCA. Building, Mechanical, and Fire Prevention Model Codes. Building Officials and Code Administrators International, Country Club Hills, IL.
- CAP. *Medical Laboratory Planning and Design*. College of American Pathologists, Northfield, IL.
- DHHS. 1999. *Biosafety in Microbiological and Biomedical Laboratories*, 4th ed. U.S. Department of Health and Human Services Publication (CDC).

- EEOC. 1992. *Americans with Disabilities Act Handbook*. Equal Employment Opportunity Commission.
- ICBO. Uniform Building, Mechanical, and Fire Prevention Model Codes. International Conference of Building Officials, Whittier, CA.
- NFPA. 1994. Hazardous Chemicals Data. ANSI/*NFPA Standard* 49-94. National Fire Protection Association, Quincy, MA.
- NFPA. 1999. Health Care Facilities. ANSI/NFPA *Standard* 99-99. National Fire Protection Association, Quincy, MA.
- NFPA. 2000. Fire Protection for Laboratories Using Chemicals. ANSI/ NFPA *Standard* 45-2000. National Fire Protection Association, Quincy, MA.
- NRC. 1989. Biosafety in the Laboratory: Prudent Practices for Handling and Disposal of Infectious Materials. National Research Council, National Academy Press, Washington, D.C.
- NRC. 1995. *Prudent Practices in the Laboratory: Handling and Disposal of Chemicals*. National Research Council, National Academy Press, Washington, D.C.
- OSHA. *Occupational Exposure to Chemicals in Laboratories*. Appendix VII, 29 CFR 1910.1450. Available from U.S. Government Printing Office, Washington, D.C.
- SEFA. 1996. *Laboratory Fume Hoods Recommended Practices*. SEFA 1.2-1996. Scientific Equipment and Furniture Association, Hilton Head, SC.

Other regulations and guidelines may apply to laboratory design. All applicable institutional, local, state, and federal requirements should be identified before design begins.

HAZARD ASSESSMENT

Laboratory operations potentially involve some hazard; nearly all laboratories contain some type of hazardous materials. The owner's designated safety officers should perform a comprehensive hazard assessment, which must be completed before the laboratory can be designed. These safety officers include, but are not limited to, the chemical hygiene officer, radiation safety officer, biological safety officer, and fire and loss prevention official. The hazard assessment should be incorporated into the chemical hygiene plan, radiation safety plan, and biological safety protocols.

Hazard study methods such as hazard and operability analysis (HAZOP) can be used to evaluate design concepts and certify that the HVAC design conforms to the applicable safety plans. The nature and quantity of the contaminant, types of operations, and degree of hazard dictate the types of containment and local exhaust devices. For functional convenience, operations posing less hazard potential are conducted in devices that use directional airflow for personnel protection (e.g., laboratory fume hoods and biological safety cabinets). However, these devices do not provide absolute containment. Operations having a significant hazard potential are conducted in devices that provide greater protection but are more restrictive (e.g., sealed glove boxes).

The design team should visit similar laboratories to assess successful design approaches and safe operating practices. Each laboratory is somewhat different. Its design must be evaluated using appropriate, current standards and practices rather than duplicating existing and possibly outmoded facilities.

DESIGN PARAMETERS

The following design parameters must be established for a laboratory space:

- Temperature and humidity, both indoor and outdoor
- Air quality from both process and safety perspectives, including the need for air filtration and special treatment (e.g., charcoal, HEPA, or other filtration of supply or exhaust air)
- Equipment and process heat gains, both sensible and latent
- Minimum ventilation rates
- Equipment and process exhaust quantities
- Exhaust and air intake locations
- Style of the exhaust device, capture velocities, and usage factors
- Need for standby equipment and emergency power
- Alarm requirements.
- Potential changes in the size and number of fume hoods
- Anticipated increases in internal loads
- Room pressurization requirements

It is important to (1) review design parameters with the safety officers and scientific staff, (2) determine limits that should not be exceeded, and (3) establish the desirable operating conditions. For areas requiring variable temperature or humidity, these parameters must be carefully reviewed with the users to establish a clear understanding of expected operating conditions and system performance.

Because laboratory HVAC systems often incorporate 100% outside air systems, the selection of design parameters has a substantial effect on capacity, first cost, and operating costs. The selection of proper and prudent design conditions is very important.

Internal Thermal Considerations

In addition to the heat gain from people and lighting, laboratories frequently have significant sensible and latent loads from equipment and processes. Often, data for equipment used in laboratories are unavailable or the equipment has been custom built. Data on heat release from animals that may be housed in the space can be found in Chapter 10 of the 2001 *ASHRAE Handbook—Fundamentals* and in Alereza and Breen (1984).

Careful review of the equipment to be used, a detailed understanding of how the laboratory will be used, and prudent judgment are required to obtain good estimates of the heat gains in a laboratory. The convective portion of heat released from equipment located within exhaust devices can be discounted. Heat from equipment that is directly vented or heat from water-cooled equipment should not be considered part of the heat released to the room. Any unconditioned makeup air that is not directly captured by an exhaust device must be included in the load calculation for the room. In many cases, additional equipment will be obtained by the time a laboratory facility has been designed and constructed. The design should allow for this additional equipment.

Internal load as measured in watts per square foot is the average continuous internal thermal load discharged into the space. It is not a tabulation of the connected electrical load because it is rare for all equipment to operate simultaneously, and most devices operate with a duty cycle that keeps the average electrical draw below the nameplate information. When tabulating the internal sensible heat load in a laboratory, the duty cycle of the equipment should be obtained from the manufacturer. This information, combined with the nameplate data for the item, may provide a more accurate assessment of the average thermal load.

The HVAC system engineer should evaluate equipment nameplate ratings, applicable use and usage factors, and overall diversity. Much laboratory equipment includes computers, automation, sample changing, or robotics; this can result in high levels of use even during unoccupied periods. The HVAC engineer must evaluate internal heat loads under all anticipated laboratory-operating modes. Because of highly variable equipment heat gain, individual laboratories should have dedicated temperature controls.

Two cases encountered frequently are (1) building programs based on generic laboratory modules and (2) laboratory spaces that are to be highly flexible and adaptive. Both situations require the design team to establish heat gain on an area basis. The values for area-based heat gain vary substantially for different types of laboratories. Heat gains of 5 to 25 W/ft^2 or more are common for laboratories with high concentrations of equipment.

Architectural Considerations

Integrating utility systems into the architectural planning, design, and detailing is essential to providing successful research facilities. The architect and the HVAC system engineer must seek an early understanding of each other's requirements and develop integrated solutions. HVAC systems may fail to perform properly if the architectural requirements are not addressed correctly. Quality assurance of the installation is just as important as proper specifications. The following play key roles in the design of research facilities:

Modular Planning. Most laboratory programming and planning is based on developing a module that becomes the base building block for the floor plan. Laboratory planning modules are frequently 10 to 12 ft wide and 20 to 30 ft deep. The laboratory modules may be developed as single work areas or combined to form multiple-station work areas. Utility systems should be arranged to reflect the architectural planning module, with services provided for each module or pair of modules, as appropriate.

Development of Laboratory Units. National Fire Protection Association (NFPA) *Standard* 45 requires that laboratory units be designated. Similarly, the International, Uniform, and Building Officials and Code Administrators International (BOCA) model codes require the development of control areas. Laboratory units or control areas should be developed, and the appropriate hazard levels should be determined early in the design process. The HVAC designer should review the requirements for maintaining separations between laboratories and note requirements for exhaust ductwork to serve only a single laboratory unit.

Additionally, NFPA *Standard* 45 requires that no fire dampers be installed in laboratory exhaust ductwork. Building codes offer no relief from maintaining required floor-to-floor fire separations. These criteria and the proposed solutions should be reviewed early in the design process with the appropriate building code officials. The combination of the two requirements commonly necessitates the construction of dedicated fire-rated shafts from each occupied floor to the penthouse or building roof.

Provisions for Adaptability and Flexibility. Research objectives frequently require changes in laboratory operations and programs. Thus, laboratories must be flexible and adaptable, able to accommodate these changes without significant modifications to the infrastructure. For example, the utility system design can be flexible enough to supply ample cooling to support the addition of heat-producing analytical equipment without requiring modifications to the HVAC system. Adaptable designs should allow programmatic research changes that require modifications to the laboratory's infrastructure within the limits of the individual laboratory area and/or interstitial and utility corridors. For example, an adaptable design would allow the addition of a fume hood without requiring work outside that laboratory space. The degree of flexibility and adaptability for which the laboratory HVAC system is designed should be determined from discussion with the researchers, laboratory programmer, and laboratory planner. The HVAC designer should have a clear understanding of these requirements and their financial impact.

Early Understanding of Utility Space Requirements. The amount and location of utility space are significantly more important in the design of research facilities than in that of most other buildings. The available ceiling space and the frequency of vertical distribution shafts are interdependent and can significantly affect the architectural planning. The HVAC designer must establish these parameters early, and the design must reflect these constraints. The designer should review alternative utility distribution schemes, weighing their advantages and disadvantages.

High-Quality Envelope Integrity. Laboratories that have stringent requirements for the control of temperature, humidity, relative static pressure, and background particle count generally require architectural features to allow the HVAC systems to perform properly. The building envelope may need to be designed to handle relatively high levels of humidification and slightly negative building pressure without moisture condensation in the winter or excessive infiltration. Some of the architectural features that the HVAC designer should evaluate include

- Vapor barriers—position, location, and kind
- Insulation—location, thermal resistance, and kind
- Window frames and glazing
- Caulking
- Internal partitions—their integrity in relation to air pressure, vapor barriers, and insulation value
- Finishes—vapor permeability and potential to release particles into the space
- Doors
- Air locks

Air Intakes and Exhaust Locations. Mechanical equipment rooms and their air intakes and exhaust stacks must be located to avoid intake of fumes into the building. As with other buildings, air intake locations must be chosen to minimize fumes from loading docks, cooling tower discharge, vehicular traffic, etc.

LABORATORY EXHAUST AND CONTAINMENT DEVICES

FUME HOODS

The Scientific Equipment and Furniture Association (SEFA 1996) defines a laboratory fume hood as "a ventilated enclosed work space intended to capture, contain, and exhaust fumes, vapors, and particulate matter generated inside the enclosure. It consists basically of side, back and top enclosure panels, a floor or counter top, an access opening called the face, a sash(es), and an exhaust plenum equipped with a baffle system for airflow distribution. Figure 1 shows the basic elements of a general-purpose benchtop fume hood.

Fume hoods may be equipped with a variety of accessories, including internal lights, service outlets, sinks, air bypass openings, airfoil entry devices, flow alarms, special linings, ventilated base storage units, and exhaust filters. Under counter cabinets for storage of flammable materials require special attention to ensure safe installation. NFPA *Standard* 30, Flammable and Combustible Liquids Code, does not recommend venting these cabinets; however, ventilation is often required to avoid accumulation of toxic or hazardous vapors. Ventilation of these cabinets by a separately ducted supply and exhaust that will maintain the temperature rise of the cabinet interior within the limits defined by NFPA *Standard* 30 should be considered.

Types of Fume Hoods

The following are the primary types of fume hoods and their applications:

Standard (approximately constant-volume airflow with variable face velocity). Hood that meets basic SEFA definition. Sash may be vertical, horizontal, or combination.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.

Bypass (approximately constant-volume airflow with approximately constant face velocity). Standard vertical sash hood modified with openings above and below the sash. The openings are sized to minimize the change in the face velocity, which is generally to 3 or 4 times the full-open velocity, as the sash is lowered.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.

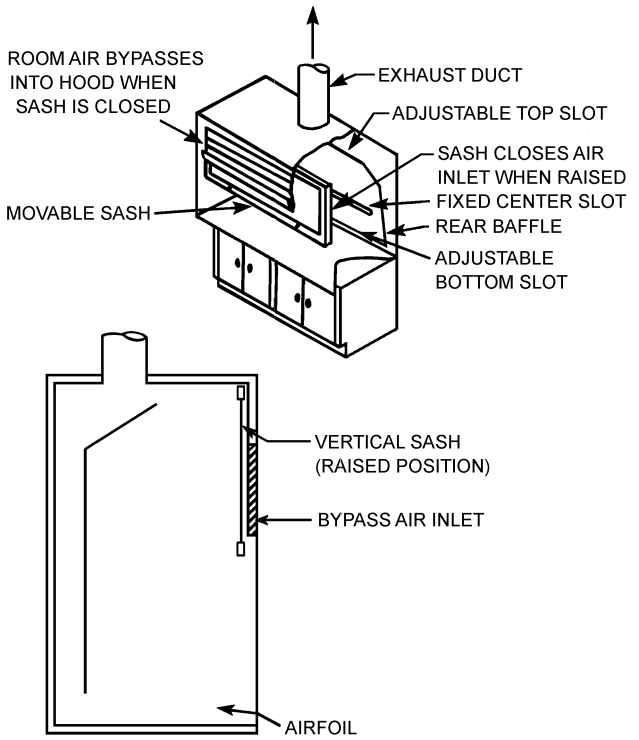

Fig. 1 Bypass Fume Hood with Vertical Sash and Bypass Air Inlet

Variable Volume (constant face velocity). Hood has an opening or bypass designed to provide a prescribed minimum air intake when the sash is closed and an exhaust system designed to vary airflow in accordance with sash opening. Sash may be vertical, horizontal, or a combination of both.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.

Auxiliary Air (approximately constant-volume airflow with approximately constant face velocity). A plenum above the face receives air from a secondary air supply that provides partially conditioned or unconditioned outside air.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.

Note: Many organizations restrict the use of this type of hood.

Process (approximately constant-volume airflow with approximately constant face velocity). Standard hood without a sash. By some definitions, this is not a fume hood. Considered a ventilated enclosure.

Application: Process laboratories—intermittent use. Low-hazard processes; known procedures.

Radioisotope. Standard hood with special integral work surface, linings impermeable to radioactive materials, and structure strong enough to support lead shielding bricks. The interior must be constructed to prevent radioactive material buildup and allow complete cleaning. The ductwork should have flanged neoprene gasketed joints with quick disconnect fasteners that can be readily dismantled for decontamination. High-efficiency particulate air (HEPA) and/or charcoal filters may be needed in the exhaust duct.

Application: Process and research laboratories using radioactive isotopes.

Perchloric Acid. Standard hood with special integral work surfaces, coved corners, and non-organic lining materials. Perchloric acid is an extremely active oxidizing agent. Its vapors can form unstable deposits in the ductwork that present a potential explosion hazard. To alleviate this hazard, the exhaust system must be equipped with an internal water washdown and drainage system, and the ductwork must be constructed of smooth, impervious, cleanable materials that are resistant to acid attack. The internal washdown system must completely flush the ductwork, exhaust fan, discharge stack, and fume hood inner surfaces. The ductwork should be kept as short as possible with minimum elbows. Perchloric acid exhaust systems with longer duct runs may need a zoned washdown system to avoid water flow rates in excess of the capacity to drain the water from the hood. Because perchloric acid is an extremely active oxidizing agent, organic materials should not be used in the exhaust system in places such as joints and gaskets. Ducts should be constructed of a stainless steel material, with a chromium and nickel content not less than that of 316 stainless steel, or of a suitable nonmetallic material. Joints should be welded and ground smooth. A perchloric acid exhaust system should only be used for work involving perchloric acid.

Application: Process and research laboratories using perchloric acid. Mandatory use because of explosion hazard.

California. Special hood with sash openings on multiple sides (usually horizontal).

Application: For enclosing large and complex research apparatus that require access from two or more sides.

Walk-In. Standard hood with sash openings to the floor. Sash can be either horizontal or vertical.

Application: For enclosing large or complex research apparatus. Not designed for personnel to enter while operations are in progress.

Distillation. Standard fume hood with extra depth and 1/3- to 1/2-height benches.

Application: Research laboratory. For enclosing tall distillation apparatus.

Canopy. Open hood with an overhead capture structure.

Application: Not a true fume hood. Useful for heat or water vapor removal from some work areas. Not to be substituted for a fume hood. Not recommended when workers must bend over the source of heat or water vapor.

Fume Hood Sash Configurations

The work opening has operable glass sash(es) for observation and shielding. A sash may be vertically operable, horizontally operable, or a combination of both. A vertically operable sash can incorporate single or multiple vertical panels. A horizontally operable sash incorporates multiple panels that slide in multiple tracks, allowing the open area to be positioned across the face of the hood. The combination of a horizontally operable sash mounted within a single vertically operable sash section allows the entire hood face to be opened for setup. Then the opening area can be limited by closing the vertical panel, with only the horizontally sliding sash sections used during experimentation. Either multiple vertical sash sections or the combination sash arrangement allow the use of larger fume hoods with limited opening areas, resulting in reduced exhaust airflow requirements. Fume hoods with vertically rising sash sections should include provisions around the sash to prevent the bypass of ceiling plenum air into the fume hood.

Fume Hood Performance

Containment of hazards in a fume hood is based on the principle that a flow of air entering at the face of the fume hood, passing

through the enclosure, and exiting at the exhaust port prevents the escape of airborne contaminants from the hood into the room.

The following variables affect the performance of the fume hood:

- Face velocity
- Size of face opening
- Sash position
- Shape and configuration of entrance
- Shape of any intermediate posts
- Inside dimensions and location of work area relative to face area
- Location of service fittings inside the fume hood
- Size and number of exhaust ports
- Back baffle and exhaust plenum arrangement
- Bypass arrangement, if applicable.
- Auxiliary air supply, if applicable
- Arrangement and type of replacement supply air outlets
- Air velocities near the hood
- Distance from openings to spaces outside the laboratory
- Movements of the researcher within the hood opening
- Location, size, and type of research apparatus placed in the hood
- Distance from the apparatus to the researcher's breathing zone

Air Currents. Air currents external to the fume hood can jeopardize the hood's effectiveness and expose the researcher to materials used in the hood. Detrimental air currents can be produced by

- Air supply distribution patterns in the laboratory
- Movements of the researcher
- People walking past the fume hood
- Thermal convection
- Opening of doors and windows

Caplan and Knutson (1977, 1978) conducted tests to determine the interactions between room air motion and fume hood capture velocities with respect to the spillage of contaminants into the room. Their tests indicated that the effect of room air currents is significant and of the same order of magnitude as the effect of the hood face velocity. Consequently, improper design and/or installation of the replacement air supply can lower the performance of the fume hood.

Disturbance velocities at the face of the hood should be no more than one-half and preferably one-fifth the face velocity of the hood. This is an especially critical factor in designs that use low face velocities. For example, a fume hood with a face velocity of 100 fpm could tolerate a maximum disturbance velocity of 50 fpm. If the design face velocity were 60 fpm, the maximum disturbance velocity would be 30 fpm.

To the extent possible, the fume hood should be located so that traffic flow past the hood is minimal. Also, the fume hood should be placed to avoid any air currents generated from the opening of windows and doors. To ensure the optimum placement of the fume hoods, the HVAC system designer must take an active role early in the design process.

Use of Auxiliary Air Fume Hoods. AIHA *Standard* Z9.5 discourages the use of auxiliary air fume hoods. These hoods incorporate an air supply at the fume hood to reduce the amount of room air exhausted. The following difficulties and installation criteria are associated with auxiliary air fume hoods:

- The auxiliary air supply must be introduced outside the fume hood to maintain appropriate velocities past the researcher.
- The flow pattern of the auxiliary air must not degrade the containment performance of the fume hood.
- Auxiliary air must be conditioned to avoid blowing cold air on the researcher; often the air must be cooled to maintain the required temperature and humidity within the hood. Auxiliary air can introduce additional heating and cooling loads in the laboratory.
- Only vertical sash should be used in the hood.
- Controls for the exhaust, auxiliary, and supply airstreams must be coordinated.
- Additional coordination of utilities during installation is required to avoid spatial conflicts caused by the additional duct system.
- Humidity control can be difficult: Unless auxiliary air is cooled to the dew point of the specified internal conditions, there is some degradation of humidity control; however, if such cooling is done, the rationale for using auxiliary air has been eliminated.

Fume Hood Performance Criteria. ASHRAE *Standard* 110, Method of Testing Performance of Laboratory Fume Hoods, describes a quantitative method of determining the containment performance of a fume hood. The method requires the use of a tracer gas and instruments to measure the amount of tracer gas that enters the breathing zone of a mannequin; this simulates the containment capability of the fume hood as a researcher conducts operations in the hood. The following tests are commonly used to judge the performance of the fume hood: (1) face velocity test, (2) flow visualization test, (3) large-volume flow visualization, (4) tracer gas test, and (5) sash movement test. These tests should be performed under the following conditions:

- Usual amount of research equipment in the hood; the room air balance set
- Doors and windows in their normal positions
- Fume hood sash set in varying positions to simulate both static and dynamic performance

All fume hoods should be tested annually and their performance certified. The following descriptions partially summarize the test procedures. ASHRAE *Standard* 110 provides specific requirements and procedures.

Face Velocity Test

The safety officer, engineer, and the researcher should determine the desired face velocity. The velocity is a balance between safe operation of the fume hood, airflow needed for the hood operation, and energy cost. Face velocity measurements are taken on a vertical/horizontal grid, with each measurement point representing not more than 1 ft^2. The measurements should be taken with a device that is accurate in the intended operating range, and an instrument holder should be used to improve accuracy. Computerized multipoint grid measurement devices provide the greatest accuracy.

Flow Visualization

1. Swab a strip of titanium tetrachloride along both walls and the hood deck in a line parallel to the hood face and 6 in. back into the hood. *Caution*: Titanium tetrachloride forms smoke and is corrosive to the skin and extremely irritating to the eyes and respiratory system.
2. Swab an 8 in. circle on the back of the hood. Define air movement toward the face of the hood as reverse airflow and lack of movement as dead airspace.
3. Swab the work surface of the hood, being sure to swab lines around all equipment in the hood. All smoke should be carried to the back of the hood and out.
4. Test the operation of the deck airfoil bypass by running the cotton swab under the airfoil.
5. Before going to the next test, move the cotton swab around the face of the hood; if there is any outfall, the exhaust capacity test (large capacity flow visualization) should not be made.

Large-Volume Flow Visualization

Appropriate measures should be taken prior to undertaking a smoke test to avoid accidental activation of the building's smoke detection system.

1. Ignite and place a smoke generator near the center of the work surface 6 in. behind the sash. Some smoke sources generate a jet of smoke that produces an unacceptably high challenge to the hood. Care is required to ensure that the generator does not disrupt the hood performance, leading to erroneous conclusions.

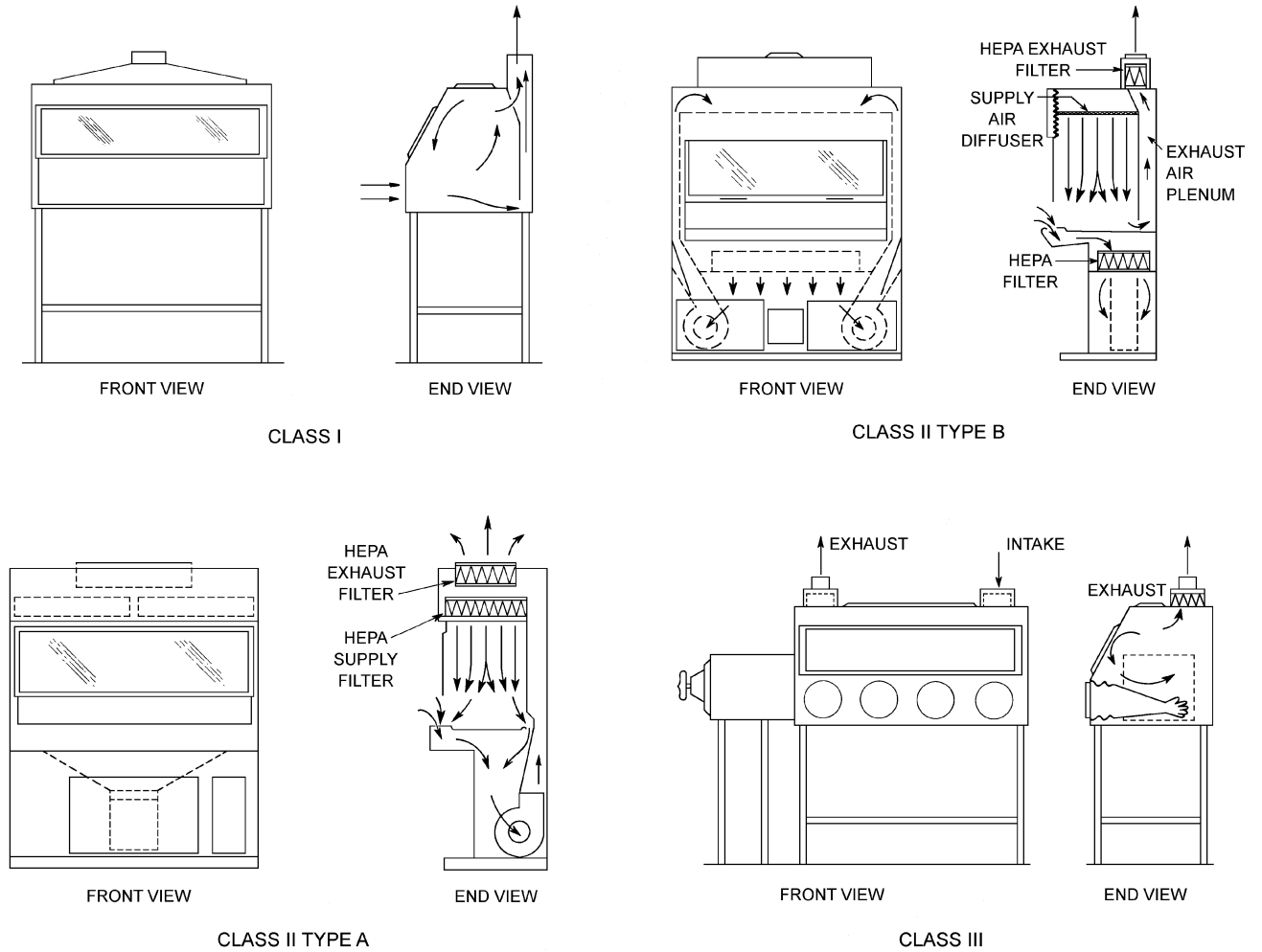

Fig. 2 Types of Biological Safety Cabinets

2. After the smoke bomb is ignited, pick it up with tongs and move it around the hood. The smoke should not be seen or smelled outside the hood.

Tracer Gas Test

1. Place the sulfur hexafluoride gas ejector in the required test locations (i.e., the center and near each side). Similarly position a mannequin with a detector in its breathing zone in the corresponding location at the hood.
2. Release the tracer gas and record measurements over a 5 min time span.
3. After testing with the mannequin is complete, remove it, traverse the hood opening with the detector probe, and record the highest measurement.

Sash Movement Test

Verify containment performance of the fume during operation of the fume hood sash as described in ASHRAE *Standard* 110.

BIOLOGICAL SAFETY CABINETS

A biological safety cabinet protects the researcher and, in some configurations, the research materials as well. Biological safety cabinets are sometimes called safety cabinets, ventilated safety cabinets, laminar flow cabinets, and glove boxes. Biological safety cabinets are categorized into six groups (several are shown in Figure 2):

Class I	Similar to chemical fume hood, no research material protection, 100% exhaust through a HEPA filter
Class II	
Type A1	70% recirculation within the cabinet; 30% exhaust through a HEPA filter; common plenum configuration; can be recirculated into the laboratory
Type B1	30% recirculation within the cabinet; 70% exhaust through a HEPA filter; separate plenum configuration, must be exhausted to the outside
Type B2	100% exhaust through a HEPA filter to the outside
Type A2	70% recirculation within the cabinet; 30% exhaust through a HEPA filter; common plenum configuration; must be exhausted to the outside
Class III	Special applications; 100% exhaust through a HEPA filter to the outside; researcher manipulates material within cabinet through physical barriers (gloves)

The researcher must make several key decisions before selecting a biological safety cabinet (Eagleston 1984). An important difference in biological safety cabinets is their ability to handle chemical vapors properly (Stuart et al. 1983). Of special concern to the HVAC

engineer are the proper placement of the biological safety cabinet in the laboratory and the room's air distribution. Rake (1978) concluded the following:

> A general rule of thumb should be that, if the cross draft or other disruptive room airflow exceeds the velocity of the air curtain at the unit's face, then problems do exist. Unfortunately, in most laboratories such disruptive room airflows are present to various extents. Drafts from open windows and doors are the most hazardous sources because they can be far in excess of 200 fpm and accompanied by substantial turbulence. Heating and air-conditioning vents perhaps pose the greatest threat to the safety cabinet because they are much less obvious and therefore seldom considered. . . . It is imperative then that all room airflow sources and patterns be considered before laboratory installation of a safety cabinet.

Class II biological safety cabinets should only be placed in the laboratory in compliance with NSF International *Standard* 49, Class II (Laminar Flow) Biohazard Cabinetry. Assistance in procuring, testing, and evaluating performance parameters of Class II biological safety cabinets is available from NSF as part of the standard. The cabinets should be located away from drafts, active walkways, and doors. The air distribution system should be designed to avoid air patterns that impinge on the cabinet.

The different biological safety cabinets have varying static pressure resistance requirements. Generally, Class II Type A1 cabinets have pressure drops ranging between 0.005 and 0.1 in. of water. Class II Type B1 cabinets have pressure drops in the range of 0.6 to 1.2 in. of water, and Class II Type B2 cabinets have pressure drops ranging from 1.5 to 2.3 in. of water. The manufacturer must be consulted to verify specific requirements.

The pressure requirements also vary based on filter loading and the intermittent operation of individual biological safety cabinets. Exhaust systems for biological safety cabinets must be designed with these considerations in mind. Care must be exercised when manifolding biological safety cabinet exhausts to ensure that the varying pressure requirements are met.

The manufacturer of the biological safety cabinet may be able to supply the transition to the duct system. The transition should include an access port for testing and balancing and an airtight damper for decontamination. As with any containment ductwork, high-integrity duct fabrication and joining systems are necessary.

Biological safety cabinets may require periodic decontamination before service and filter replacement. During the decontamination procedure, the cabinet must be isolated or sealed from the laboratory and the exhaust system. The responsible safety officer should be consulted to determine the need for and placement of isolation dampers to facilitate decontamination operations. If provisions for decontamination are necessary, the ventilation system design should maintain laboratory airflow and pressure during the decontamination procedure.

Class I Cabinets

The Class I cabinet is a partial containment device designed for research operations with low- and moderate-risk etiologic agents. It does not provide protection for the materials used in the cabinet. Room air flows through a fixed opening and prevents aerosols that may be generated within the cabinet enclosure from escaping into the room. Depending on cabinet usage, air exhausted through the cabinet may be HEPA filtered prior to being discharged into the exhaust system. The fixed opening through which the researcher works is usually 8 in. high. To provide adequate personnel protection, the air velocity through the fixed opening is usually at least 75 fpm.

If approved by the appropriate safety officer, it is possible to modify the Class I cabinet to contain chemical carcinogens by adding appropriate exhaust air treatment and increasing the velocity through the opening to 100 fpm. Large pieces of research equipment can be placed in the cabinet if adequate shielding is provided.

The Class I cabinet is not appropriate for containing systems that are vulnerable to airborne contamination because the air flowing into the cabinet is untreated. Also, the Class I cabinet is not recommended for use with highly infectious agents because an interruption of the inward airflow may allow aerosolized particles to escape.

Class II Cabinets

Class II cabinets provide protection to personnel, product, and the environment. The cabinets feature an open front with inward airflow and HEPA-filtered recirculated and exhaust air. Microbiological containment, product protection, and cross-contamination performance is established for certain cabinets by NSF International's *Standard* 49.

The Class II Type A1 cabinet has a fixed opening with a minimum inward airflow velocity of 75 fpm. The average downward velocity is established by the manufacturer and is typically in the range of 50 to 80 fpm. The Class II Type A1 cabinet is suitable for use with agents meeting Biosafety Level 2 criteria (DHHS 1999), and, if properly certified, can meet Biosafety Level 3. However, because approximately 70% of the airflow is recirculated, the cabinet is not suitable for use with flammable, toxic, or radioactive agents.

The Class II Type B1 cabinet has a vertical sliding sash and maintains an inward airflow of 100 fpm at a sash opening of 8 in.. The average downward velocity of the internal airflow is typically in the range of 50 to 80 fpm. The Class II Type B1 cabinet is suitable for use with agents meeting Biosafety Level 3. Approximately 70% of the internal airflow is exhausted through HEPA filters; this allows the use of biological agents treated with limited quantities of toxic chemicals and trace amounts of radionuclides, provided the work is performed in the direct exhaust area of the cabinet.

The Class II Type B2 cabinet maintains an inward airflow velocity of 100 fpm through the work opening. The cabinet is 100% exhausted through HEPA filters to the outdoors; all downward-velocity air is drawn from the laboratory or other supply source and is HEPA filtered before being introduced into the workspace. The Class II Type B2 cabinet may be used for the same level of work as the Class II Type B1 cabinet. In addition, the design permits use of toxic chemicals and radionuclides in microbiological studies.

The Class II Type A2 cabinet maintains an inward airflow velocity of 100 fpm and is similar in performance to the Class II Type A1 cabinet.

In Class II Type A2 cabinets, exhaust air delivered to the outlet of the cabinet by internal blowers must be handled by the laboratory exhaust system. This arrangement requires a delicate balance between the cabinet and the laboratory's exhaust system, and it may incorporate a thimble connection between the cabinet and the laboratory exhaust ductwork. Thimble (or canopy) connections incorporate an air gap between the biological safety cabinet and the exhaust duct. The purpose of the air gap is to buffer the effect of any exhaust system fluctuations on the biological safety cabinet airflow. The exhaust system must pull more air than is exhausted by the biological safety cabinet to make air flow in through the gap. The designer should confirm the amount of air to be drawn through the air gap. A minimum flow is required to provide the specified level of containment, and a maximum flow cannot be exceeded without causing an imbalance through aspiration. In the event of an exhaust system failure, the air gap allows the cabinet to maintain safe intake velocity by exhausting HEPA-filtered air through the air gap.

Class II Type B1 and Type B2 cabinets rely on the building exhaust system to pull the air from the cabinet's workspace and through the exhaust HEPA filters. The pressure resistance that must be overcome by the building exhaust system can be obtained from the cabinet manufacturer. Because containment in this type of cabinet depends on the building's exhaust system, the exhaust fan(s) should have redundant backups.

Class III Cabinets

The Class III cabinet is a gastight, negative pressure containment system that physically separates the agent from the worker. These cabinets provide the highest degree of personnel protection. Work is performed through arm-length rubber gloves attached to a sealed front panel. Room air is drawn into the cabinet through HEPA filters. Class III cabinets should be maintained at 0.5 in. of water below ambient pressure. Exhaust flow rate should provide a minimum of 100 fpm inward containment velocity through a glove port opening in the event of a glove being inadvertently removed. HEPA filtration or incineration before discharge to the atmosphere removes or destroys particulate material entrained in the exhaust air. A Class III system may be designed to enclose and isolate incubators, refrigerators, freezers, centrifuges, and other research equipment. Double-door autoclaves, liquid disinfectant dunk tanks, and pass boxes are used to transfer materials into and out of the cabinet.

Class III systems can contain highly infectious materials and radioactive contaminants. Although there are operational inconveniences with these cabinets, they are the equipment of choice when a high degree of personnel protection is required. It should be noted that explosions have occurred in Class III cabinets used for research involving volatile substances.

MISCELLANEOUS EXHAUST DEVICES

Snorkels are used in laboratories to remove heat or nontoxic particles that may be generated from benchtop research equipment. Snorkels usually have funnel-shaped inlet cones connected to 3 to 6 in. diameter flexible or semi-flexible ductwork extending from the ceiling to above the benchtop level.

Typically, **canopy hoods** are used to remove heat or moisture generated by a specific piece of research apparatus (e.g., steam sterilizer) or process. Canopy hoods cannot contain hazardous fumes adequately to protect the researcher.

The laboratory, if maintained at negative relative static pressure, provides a second level of containment, protecting occupied spaces outside of the laboratory from operations and processes undertaken therein.

LAMINAR FLOW CLEAN BENCHES

Laminar flow clean benches are available in two configurations—horizontal (crossflow) and vertical (downflow). Both configurations filter the supply air and usually discharge the air out the front opening into the room. Clean benches protect the experiment or product but do not protect the researcher; therefore, they should not be used with any potentially hazardous or allergenic substances. Clean benches are not recommended for any work involving hazardous biological, chemical, or radionuclide materials.

COMPRESSED GAS STORAGE AND VENTILATION

Gas Cylinder Closets

Most laboratory buildings require storage closets for cylinders of compressed gases, which may be inert, flammable, toxic, corrosive, or poisonous. The requirements for storage and ventilation are covered in building codes and NFPA standards and codes. Water sprinklers are usually required, but other types of fire suppression may be needed based on the gases stored. Explosion containment requires a separate structural study, and closets generally require an outside wall for venting. One design used by a large chemical manufacturer to house gases with explosion potential specifies a completely welded 0.25 in. steel inner liner for the closet, heavy-duty door latches designed to hold under the force of an internal explosion, and venting out the top of the closet.

The closet temperature should not exceed 125°F per NFPA *Standard* 55. Ventilation for cylinder storage is established in NFPA *Standard* 55 at a minimum of 1 cfm/ft^2. Ventilation rates can be calculated by determining both the amount of gas that could be released by complete failure of the cylinder outlet piping connection and the time the release would take, and then finding the dilution airflow required to reduce any hazard below the maximum allowable limit. Design principles for biohazardous materials may be different than for chemical hazards. An investigation for biohazard containment can start with NFPA *Standard* 99, Health Care Facilities.

Ventilation air is usually exhausted from the closet; makeup air comes from the surrounding space through openings in and around the door or through a transfer duct. That makeup air must be added into the building air balance. Ventilation for a closet to contain materials with explosion potential must be carefully designed, with safety considerations taken into account. NFPA *Standard* 68 is a reference on explosion venting.

Cylinder closet exhausts should be connected through a separate duct system to a dedicated exhaust fan or to a manifold system in which constant volume can be maintained under any possible manifold condition. A standby source of emergency power should be considered for the exhaust system fan(s).

Gas Cylinder Cabinets

Compressed gases that present a physical or health hazard are often placed in premanufactured gas cylinder cabinets. Gas cylinder cabinets are available for single-, dual-, or triple-cylinder configurations and are commonly equipped with valve manifolds, fire sprinklers, exhaust connections, access openings, and operational and safety controls. The engineer must fully understand safety, material, and purity requirements associated with specific compressed gases when designing and selecting cylinder cabinets and the components that make up the compressed gas handling system.

Exhaust from the gas cylinder cabinets is provided at a high rate. Air is drawn into the gas cylinder cabinet from the surrounding space through a filtered opening, usually on the lower front of the cylinder cabinet. Depending on the specific gas in the cabinet, the exhaust system may require emission control equipment and a source of emergency power.

LABORATORY VENTILATION

The total airflow rate for a laboratory is dictated by one of the following:

- Total amount of exhaust from containment and exhaust devices
- Cooling required to offset internal heat gains
- Minimum ventilation rate requirements

Fume hood exhaust requirements (including evaluation of alternate sash configurations as described in the section on Fume Hoods) must be determined in consultation with the safety officers. The HVAC engineer must determine the expected heat gains from the research equipment after consulting with the research staff (see the section on Internal Thermal Considerations).

Minimum airflow rates are generally in the range of 6 to 10 air changes per hour when the space is occupied; however, some spaces (e.g., animal holding areas) may have minimum airflow rates established by specific standards or by internal facility policies. For example, the National Institutes of Health (NIH 1999a, 1999b) recommend a minimum of 6 air changes per hour for occupied laboratories but a minimum of 15 air changes per hour for animal housing and treatment areas. The maximum airflow rate for the laboratory should be reviewed to ensure that appropriate supply air delivery methods are chosen such that supply airflows do not impede the performance of the exhaust devices. Laboratory ventilation systems can be arranged for either constant-volume or variable-volume airflow. The specific type should be selected with the research staff,

safety officers, and maintenance personnel. Special attention should be given to unique areas such as glass washing areas, hot and cold environmental rooms and labs, fermentation rooms, and cage washing rooms. Emergency power systems to operate the laboratory ventilation equipment should be considered based on hazard assessment or other specific requirements. Care should be taken to ensure that an adequate amount of makeup air is available whenever exhaust fans are operated on emergency power. Additional selection criteria are described in the sections on Hazard Assessment and Operation and Maintenance.

Usage Factor

In many laboratories, all hoods and safety cabinets are seldom needed at the same time. A system usage factor represents the maximum number of exhaust devices with sashes open or in use simultaneously. The system usage factor depends on the

- Type and size of facility
- Total number of fume hoods
- Number of fume hoods per researcher
- Airflow diversity
- Type of fume hood controls
- Fume hood sash configuration and minimum airflow required
- Type of laboratory ventilation systems
- Number of devices that must operate continuously due to chemical storage requirements or contamination prevention
- Number of current and projected research programs

Usage factors should be applied carefully when sizing equipment. For example, teaching laboratories may have a usage factor of 100% when occupied by students.

If too low a usage factor is selected, design airflow and containment performance cannot be maintained. It is usually expensive and disruptive to add capacity to an operating laboratory's supply or exhaust system. Detailed discussions with research staff are required to ascertain maximum usage factors as well as likely future requirements.

Noise

Noise level in the laboratory should be considered at the beginning of the design so that noise criterion (NC) levels suitable for scientific work can be achieved. For example, at the NIH, sound levels of NC 40 to 45 (including fume hoods) are required in regularly occupied laboratories. The requirement is relaxed to NC 55 for instrument rooms. If noise criteria are not addressed as part of the design, NC levels can be 65 or greater, which is unacceptable to most occupants. Sound generated by the building HVAC equipment should be evaluated to ensure that excessive levels do not escape to the outdoors. Remedial correction of excessive sound levels can be difficult and expensive. See Chapter 47 for more information.

SUPPLY AIR SYSTEMS

Supply air systems for laboratories provide the following:

- Thermal comfort for occupants
- Minimum and maximum airflow rates
- Replacement for air exhausted through fume hoods, biological safety cabinets, or other exhaust devices
- Space pressurization control
- Environmental control to meet process or experimental criteria

The design parameters must be well defined for selection, sizing, and layout of the supply air system. Installation and setup should be verified as part of the commissioning process. Design parameters are covered in the section on Design Parameters, and commissioning is covered in the section on Commissioning. Laboratories in which chemicals and compressed gases are used generally require nonrecirculating or 100% outside air supply systems. The selection of 100% outside air supply systems versus return air systems should be made as part of the hazard assessment process, which is discussed in the section on Hazard Assessment. A 100% outside air system must have a very wide range of heating and cooling capacity, which requires special design and control.

Supply air systems for laboratories include constant-volume, high-low volume, and variable-volume systems that incorporate either single-duct reheat or dual-duct configurations, with distribution through low-, medium-, or high-pressure ductwork.

Filtration

Filtration for the air supply depends on the requirements of the laboratory. Conventional chemistry and physics laboratories commonly use 85% dust spot efficient filters (ASHRAE *Standard* 52.1). Biological and biomedical laboratories usually require 85 to 95% dust spot efficient filtration. HEPA filters should be provided for spaces where research materials or animals are particularly susceptible to contamination from external sources. HEPA filtration of the supply air is necessary for such applications as environmental studies, studies involving specific pathogen-free research animals or nude mice, dust-sensitive work, and electronic assemblies. In many instances, biological safety cabinets or laminar flow clean benches (which are HEPA filtered) may be used rather than HEPA filtration for the entire laboratory.

Air Distribution

Air supplied to a laboratory must be distributed to keep temperature gradients and air currents to minimum. Air outlets (preferably nonaspirating diffusers) must not discharge into the face of a fume hood, a biological safety cabinet, or an exhaust device. Acceptable room air velocities are covered in the sections on Fume Hoods and Biological Safety Cabinets. Special techniques and diffusers are often needed to introduce the large air quantities required for a laboratory without creating disturbances at exhaust devices.

EXHAUST SYSTEMS

Laboratory exhaust systems remove air from containment devices and from the laboratory itself. The exhaust system must be controlled and coordinated with the supply air system to maintain correct pressurization. Additional information on the control of exhaust systems is included in the section on Control. Design parameters must be well defined for selection, sizing, and layout of the exhaust air system. Installation and setup should be verified as part of the commissioning process. See the sections on Design Parameters and Commissioning. Laboratory exhaust systems should be designed for high reliability and ease of maintenance. This can be achieved by providing multiple exhaust fans that are not necessarily redundant or by sectionalizing equipment so that maintenance work may be performed on an individual exhaust fan while the system is operating. Another option is to use predictive maintenance procedures to detect problems prior to failure and to allow for scheduled shutdowns for maintenance. To the extent possible, components of exhaust systems should allow maintenance without exposing maintenance personnel to the exhaust airstream. Access to filters and the need for bag-in, bag-out filter housings should be considered during the design process.

Depending on the effluent of the processes being conducted, the exhaust airstream may require filtration, scrubbing, or other emission control to remove environmentally hazardous materials. Any need for emission control devices must be determined early in the design so that adequate space can be provided and cost implications can be recognized.

Types of Exhaust Systems

Laboratory exhaust systems can be constant-volume, variable-volume, or high-low volume systems with low-, medium-, or high-pressure ductwork, depending on the static pressure of the system. Each fume hood may have its own exhaust fan, or fume hoods may be manifolded and connected to one or more common central exhaust fans. Maintenance, functional requirements, and safety must be considered when selecting an exhaust system. Part of the hazard assessment analysis is to determine the appropriateness of variable-volume systems and the need for individually ducted exhaust systems. Laboratories with a high hazard potential should be analyzed carefully before variable-volume airflow is selected, because minimum air flow requirements could affect the design criteria.Airflow monitoring and pressure-independent control may be required even with constant-volume systems. In addition, fume hoods or other devices in which extremely hazardous or radioactive materials are used should receive special review to determine whether they should be connected to a manifolded exhaust system.

All exhaust devices installed in a laboratory are seldom used simultaneously at full capacity. This allows the HVAC engineer to conserve energy and, potentially, to reduce equipment capacities by installing a variable-volume system that includes an overall system usage factor. The selection of an appropriate usage factor is discussed in the section on Usage Factor.

Manifolded Exhaust Systems. These can be classified as pressure-dependent or pressure-independent. **Pressure-dependent systems** are constant-volume only and incorporate manually adjusted balancing dampers for each exhaust device. If an additional fume hood is added to a pressure-dependent exhaust system, the entire system must be rebalanced, and the speed of the exhaust fans may need to be adjusted. Because pressure-independent systems are more flexible, pressure-dependent systems are not common in current designs.

A **pressure-independent system** can be constant-volume, variable-volume, or a mix of the two. It incorporates pressure-independent volume regulators with each device. The system offers two advantages: (1) the flexibility to add exhaust devices without having to rebalance the entire system and (2) variable-volume control.

The volume regulators can incorporate either direct measurement of the exhaust airflow rate or positioning of a calibrated pressure-independent air valve. The input to the volume regulator can be (1) a manual or timed switch to index the fume hood airflow from minimum to operational airflow, (2) sash position sensors, (3) fume hood cabinet pressure sensors, or (4) velocity sensors. The section on Control covers this topic in greater detail. Running many exhaust devices into the manifold of a common exhaust system offers the following potential benefits:

- Lower ductwork cost
- Fewer pieces of equipment to operate and maintain
- Fewer roof penetrations and exhaust stacks
- Opportunity for energy recovery
- Centralized locations for exhaust discharge
- Ability to take advantage of exhaust system diversity
- Ability to provide a redundant exhaust system by adding one spare fan per manifold

Individually Ducted Exhaust Systems. These comprise a separate duct, exhaust fan, and discharge stack for each exhaust device or laboratory. The exhaust fan can be single-speed, multiple-speed, or variable-speed and can be configured for constant volume, variable volume, or a combination of the two. An individually ducted exhaust system has the following potential benefits:

- Provision for installation of special exhaust filtration or treatment systems
- Customized ductwork and exhaust fan corrosion control for specific applications
- Provision for selected emergency power backup
- Simpler initial balancing

Maintaining correct flow at each exhaust fan requires (1) periodic maintenance and balancing and (2) consideration of the flow rates with the fume hood sash in different positions. One problem encountered with individually ducted exhaust systems occurs when an exhaust fan is shut down. In this case, air can be drawn in reverse flow through the exhaust ductwork into the laboratory because the laboratory is maintained at a negative pressure.

A challenge in designing independently ducted exhaust systems for multistory buildings is to provide extra vertical ductwork, extra space, and other provisions for the future installation of additional exhaust devices. In multistory buildings, dedicated fire-rated shafts may be required from each floor to the penthouse or roof level. This issue should be evaluated in conjunction with the requirements of the relevant fire code. As a result, individually ducted exhaust systems (or vertically manifolded systems) consume greater floor space than horizontally manifolded systems. However, less height between floors may be required.

Ductwork Leakage

Ductwork should have low leakage rates and should be tested to confirm that the specified leakage rates have been attained. Leaks from positive pressure exhaust ductwork can contaminate the building, so they must be kept to a minimum. Designs that minimize the amount of positive-pressure ductwork are desirable. All positive-pressure ductwork should be of the highest possible integrity. The fan discharge should connect directly to the vertical discharge stack. Careful selection and proper installation of airtight flexible connectors at the exhaust fans are essential. Some feel that flexible connectors should be used on the exhaust fan inlet only. If flexible connectors are used on the discharge side of the exhaust fan, they must be of high quality and included on a preventative maintenance schedule because a connector failure could result in the leakage of hazardous fumes into the equipment room. Another viewpoint contends that the discharge side of the exhaust fan should be hard connected to the ductwork without the use of flexible connectors. The engineer should evaluate these details carefully. The potential for vibration and noise transmission must also be considered. Machine rooms that house exhaust fans should be ventilated to minimize exposure to exhaust effluent (e.g., leakage from the shaft openings of exhaust fans).

Containment Device Leakage

Leakage of the containment devices themselves must also be considered. For example, in vertical sash fume hoods, the clearance to allow sash movement creates an opening from the top of the fume hood into the ceiling space or area above. The air introduced through this leakage path also contributes to the exhaust airstream. The amount that such leakage sources contribute to the exhaust airflow depends on the fume hood design. Edge seals can be placed around sash tracks to minimize leaks. Although the volumetric flow of air exhausted through a fume hood is based on the actual face opening, appropriate allowances for air introduced through paths other than the face opening must be included.

Materials and Construction

The selection of materials and the construction of exhaust ductwork and fans depend on the following:

- Nature of the effluents
- Ambient temperature
- Ambient relative humidity
- Effluent temperature
- Length and arrangement of duct runs

- Constant or intermittent flow
- Flame spread and smoke developed ratings
- Duct velocities and pressures

Effluents may be classified generically as organic or inorganic chemical gases, vapors, fumes, or smoke; and qualitatively as acids, alkalis (bases), solvents, or oils. Exhaust system ducts, fans, dampers, flow sensors, and coatings are subject to (1) corrosion, which destroys metal by chemical or electrochemical action; (2) dissolution, which destroys materials such as coatings and plastics; and (3) melting, which can occur in certain plastics and coatings at elevated temperatures.

Common reagents used in laboratories include acids and bases. Common organic chemicals include acetone, ether, petroleum ether, chloroform, and acetic acid. The HVAC engineer should consult with the safety officer and scientists because the specific research to be conducted determines the chemicals used and therefore the necessary duct material and construction.

The ambient temperature in the space housing the ductwork and fans affects the condensation of vapors in the exhaust system. Condensation contributes to the corrosion of metals, and the chemicals used in the laboratory may further accelerate corrosion.

Ducts are less subject to corrosion when runs are short and direct, the flow is maintained at reasonable velocities, and condensation is avoided. Horizontal ductwork may be more susceptible to corrosion if condensate accumulates in the bottom of the duct. Applications with moist airstreams (cage washers, sterilizers, etc.) may require condensate drains that are connected to chemical sewers. The design should include provisions to minimize joint or seam corrosion problems.

If flow through the ductwork is intermittent, condensate may remain for longer periods because it will not be able to reevaporate into the airstream. Moisture can also condense on the outside of ductwork exhausting cold environmental rooms.

Flame spread and smoke developed ratings, which are specified by codes or insurance underwriters, must also be considered when selecting duct materials. In determining the appropriate duct material and construction, the HVAC engineer should

- Determine the types of effluents (and possibly combinations) handled by the exhaust system
- Classify effluents as either organic or inorganic, and determine whether they occur in the gaseous, vapor, or liquid state
- Classify decontamination materials
- Determine the concentration of the reagents used and the temperature of the effluents at the hood exhaust port (this may be impossible in research laboratories)
- Estimate the highest possible dew point of the effluent
- Determine the ambient temperature of the space housing the exhaust system
- Estimate the degree to which condensation may occur
- Determine whether flow will be constant or intermittent (intermittent flow conditions may be improved by adding time delays to run the exhaust system long enough to dry the duct interior prior to shutdown)
- Determine whether insulation, watertight construction, or sloped and drained ductwork are required
- Select materials and construction most suited for the application

Considerations in selecting materials include resistance to chemical attack and corrosion, reaction to condensation, flame and smoke ratings, ease of installation, ease of repair or replacement, and maintenance costs.

Appropriate materials can be selected from standard references and by consulting with manufacturers of specific materials. Materials for chemical fume exhaust systems and their characteristics include the following:

Galvanized steel. Subject to acid and alkali attack, particularly at cut edges and under wet conditions; cannot be field welded without destroying galvanization; easily formed; low in cost.

Stainless steel. Subject to acid and chloride compound attack depending on the nickel and chromium content of the alloy. Relatively high in cost. The most common stainless steel alloys used for laboratory exhaust systems are 304 and 316. Cost increases with increasing chromium and nickel content.

Asphaltum-coated steel. Resistant to acids; subject to solvent and oil attack; high flame and smoke rating; base metal vulnerable when exposed by coating imperfections and cut edges; cannot be field welded without destroying galvanization; moderate cost.

Epoxy-coated steel. Epoxy phenolic resin coatings on mild black steel can be selected for particular characteristics and applications; they have been successfully applied for both specific and general use, but no one compound is inert or resistive to all effluents. Requires sand blasting to prepare the surface for a shop-applied coating, which should be specified as pinhole-free, and field touch-up of coating imperfections or damage caused by shipment and installation; cannot be field welded without destroying coating; cost is moderate.

Polyvinyl-coated galvanized steel. Subject to corrosion at cut edges; cannot be field welded; easily formed; moderate in cost.

Fiberglass. When additional glaze coats are used, this is particularly good for acid applications, including hydrofluoric acid. May require special fire-suppression provisions. Special attention to hanger types and spacing is needed to prevent damage.

Plastic materials. Have particular resistance to specific corrosive effluents; limitations include physical strength, flame spread and smoke developed rating, heat distortion, and high cost of fabrication. Special attention to hanger types and spacing is needed to prevent damage.

Borosilicate glass. For specialized systems with high exposure to certain chemicals such as chlorine.

FIRE SAFETY FOR VENTILATION SYSTEMS

Most local authorities have laws that incorporate NFPA *Standard* 45, Fire Protection for Laboratories Using Chemicals. Laboratories located in patient care buildings require fire standards based on NFPA *Standard* 99, Health Care Facilities. NFPA *Standard* 45 design criteria include the following:

Air balance. "The air pressure in the laboratory work areas shall be negative with respect to adjacent corridors and non-laboratory areas." (Para. 6-3.3)

Controls. "Controls and dampers . . . shall be of a type that, in the event of failure, will fail in an open position to assure a continuous draft." (Para. 6-5.7)

Diffuser locations. "The location of air supply diffusion devices shall be chosen to avoid air currents that would adversely affect performance of laboratory hoods. . . ." (Para. 6-3.4)

Fire dampers. "Automatic fire dampers shall not be used in laboratory hood exhaust systems. Fire detection and alarm systems shall not be interlocked to automatically shut down laboratory hood exhaust fans. . . ." (Para. 6-10.3)

Hood alarms. "A flow monitor shall be installed on each new laboratory hood." (Para. 6-8.7.1) "A flow monitor shall also be installed on existing hoods whenever any modifications or changes are made. . . ." (Para. 6-8.7.2)

Hood placement. "For new installations, laboratory hoods shall not be located adjacent to a single means of access or high traffic areas." (Para. 6-9.2).

Recirculation. "Air exhausted from laboratory hoods or other special local exhaust systems shall not be recirculated." (Para. 6-4.1) "Air exhausted from laboratory work areas shall not pass unducted through other areas." (Para. 6-4.3)

The designer should review the entire NFPA *Standard* 45 and local building codes to determine applicable requirements. Then the

designer should inform the other members of the design team of their responsibilities (such as proper fume hood placement). Incorrect placement of exhaust devices is a frequent design error and a common cause of costly redesign work.

CONTROL

Laboratory controls must regulate temperature and humidity, control and monitor laboratory safety devices that protect personnel, and control and monitor secondary safety barriers used to protect the environment outside the laboratory from laboratory operations (West 1978). Reliability, redundancy, accuracy, and monitoring are important factors in controlling the lab environment. Many laboratories require precise control of temperature, humidity, and airflows. Components of the control system must provide the necessary accuracy and corrosion resistance if they are exposed to corrosive environments. Laboratory controls should provide fail-safe operation, which should be defined jointly with the safety officer. A fault tree can be developed to evaluate the impact of the failure of any control system component and to ensure that safe conditions are maintained.

Thermal Control

Temperature in laboratories with a constant-volume air supply is generally regulated with a thermostat that controls the position of a control valve on a reheat coil in the supply air. In laboratories with a variable-volume ventilation system, room exhaust device(s) are generally regulated as well. The room exhaust device(s) are modulated to handle greater airflow in the laboratory when additional cooling is needed. The exhaust device(s) may determine the total supply air quantity for the laboratory.

Most microprocessor-based laboratory control systems are able to use proportional-integral-derivative (PID) algorithms to eliminate the error between the measured temperature and the temperature set point. Anticipatory control strategies increase accuracy in temperature regulation by recognizing the increased reheat requirements associated with changes in the ventilation flow rates and adjusting the position of reheat control valves before the thermostat measures space temperature changes (Marsh 1988).

Constant Air Volume (CAV) Versus Variable Air Volume (VAV) Room Airflow Control

In the past, the only option for airflow in a laboratory setting was fixed airflow. Many laboratories used chemical fume hoods controlled by on-off switches located at the hood that significantly affected the actual air balance and airflow rate in the laboratory. Now, true CAV or VAV control can be successfully achieved. The question is which system is most appropriate for a contemporary laboratory.

Many laboratories that were considered CAV systems in the past were not truly constant. Even when the fume hoods operated continuously and were of the bypass type, considerable variations in airflow could occur. Variations in airflow resulted from

- Static pressure changes due to filter loading
- Wet or dry cooling coils
- Wear of fan belts that change fan speed
- Position of chemical fume hood sash or sashes
- Outside wind speed and direction
- Position of doors and windows

Current controls can achieve good conformance to the requirements of a CAV system, subject to normal deviations in control performance (i.e., the dead band characteristics of the controller and the hysteresis present in the control system). The same is true for VAV systems, although they are more complex. Systems may be either uncontrolled or controlled. An uncontrolled CAV system can be designed with no automatic controls associated with airflow other than two-speed fan motors to reduce flow during unoccupied periods. These systems are balanced by means of manual dampers and adjustable drive pulleys. They provide reasonable airflow rates relating to design values but do not provide true CAV under varying conditions, maintain constant fume hood face velocity, or maintain relative static pressures in the spaces. For laboratories that are not considered hazardous and do not have stringent safety requirements, uncontrolled CAV may be satisfactory.

For laboratories housing potentially hazardous operations (i.e., involving toxic chemicals or biological hazards), a true CAV or VAV system ensures that proper airflow and room pressure relationships are maintained at all times. A true CAV system requires volume controls on the supply and exhaust systems.

The principal advantages of a VAV system are its ability to (1) ensure that the face velocities of chemical fume hoods are maintained within a set range and (2) reduce energy use by reducing laboratory airflow. The appropriate safety officer and the users should concur with the choice of a VAV system or a CAV system with reduced airflow during unoccupied periods. Consideration should be given to providing laboratory users with the ability to reset VAV systems to full airflow volume in the event of a chemical spill. Education of the laboratory occupants in proper use of the system is essential. The engineer should recognize that the use of variable-volume exhaust systems may result in higher concentrations of contaminants in the exhaust airstream, which may increase corrosion, which influences the selection of materials.

Room Pressure Control

In most experimental work, the laboratory apparatus or the biological vector is considered to be the primary method of containment. The facility is considered to be the secondary level of containment.

For the laboratory to act as a secondary containment barrier, the air pressure in the laboratory must be maintained slightly negative with respect to adjoining areas. Exceptions are sterile facilities or clean spaces that may need to be maintained at a positive pressure with respect to adjoining spaces. See Chapter 26, Nuclear Facilities, for examples of secondary containment for negative pressure control.

Proper isolation is accomplished through the air balance/pressure relationship to adjacent areas. The pressure relationship is either

- Negative, for hazardous isolation of hazardous or toxic operations (dirty operations), or
- Positive, for protective isolation of precious or delicate operations (clean operations).

Common methods of room pressure control include manual balancing, direct pressure, volumetric flow tracking, and cascade control. All methods modulate the same control variable—supply airflow rate; however, each method measures a different variable.

Direct Pressure Control. This method measures the pressure differential across the room envelope and adjusts the amount of supply air into the laboratory to maintain the required differential pressure. Challenges encountered include (1) maintaining the pressure differential when the laboratory door is open, (2) finding suitable sensor locations, (3) maintaining a well-sealed laboratory envelope, and (4) obtaining and maintaining accurate pressure sensing devices. The direct pressure control arrangement requires tightly constructed and compartmentalized facilities and may require a vestibule on entry/exit doors. Engineering parameters pertinent to envelope integrity and associated flow rates are difficult to predict.

Because direct pressure control works to maintain the pressure differential, the control system automatically reacts to transient disturbances. Entry/exit doors may need a switch to disable the control system when they are open. Pressure controls recognize and

compensate for unquantified disturbances such as stack effects, infiltration, and influences of other systems in the building. Expensive, complex controls are not required, but the controls must be sensitive and reliable. In non-corrosive environments, controls can support a combination of exhaust applications, and they are insensitive to minimum duct velocity conditions. Successful pressure control provides the desired directional airflow but cannot guarantee a specific volumetric flow differential.

Volumetric Flow Tracking Control. This method measures both the exhaust and supply airflow and controls the amount of supply air to maintain the desired pressure differential. Volumetric control requires that the air at each supply and exhaust point be controlled. It does not recognize or compensate for unquantified disturbances such as stack effects, infiltration, and influences of other systems in the building. Flow tracking is essentially independent of room door operation. Engineering parameters are easy to predict, and extremely tight construction is not required. Balancing is critical and must be addressed across the full operating range.

Controls may be located in corrosive and contaminated environments; however, the controls may be subject to fouling, corrosive attack, and/or loss of calibration. Flow measurement controls are sensitive to minimum duct velocity conditions. Volumetric control may not guarantee directional airflow.

Cascade Control. This method measures the pressure differential across the room envelope to reset the flow tracking differential set point. Cascade control includes the merits and problems of both direct pressure control and flow tracking control; however, first cost is greater and the control system is more complex to operate and maintain.

Fume Hood Control

Criteria for fume hood control differ depending on the type of hood. The exhaust volumetric flow is kept constant for standard, auxiliary air, and air-bypass fume hoods. In variable-volume fume hoods, the exhaust flow is varied to maintain a constant face velocity. Selection of the fume hood control method should be made in consultation with the safety officer.

Constant-volume fume hoods can further be split into either pressure-dependent or pressure-independent systems. Although simple in configuration, the pressure-dependent system is unable to adjust the damper position in response to any fluctuation in system pressure across the exhaust damper.

Variable-volume fume hood control strategies can be grouped into two categories. The first either measures the air velocity entering a small sensor in the wall of the fume hood or determines face velocity by other techniques. The measured variable is used to infer the average face velocity based on an initial calibration. This calculated face velocity is then used to modulate the exhaust flow rate to maintain the desired face velocity.

The second category of variable-volume fume hood control measures the fume hood sash opening and computes the exhaust flow requirement by multiplying the sash opening by the face velocity set point. The controller then adjusts the exhaust device (e.g., by a variable-frequency drive on the exhaust fan or a damper) to maintain the desired exhaust flow rate. The control system may measure the exhaust flow for closed-loop control, or it may not measure exhaust flow in an open-loop control by using linear calibrated flow control dampers.

STACK HEIGHTS AND AIR INTAKES

Laboratory exhaust stacks should release effluent to the atmosphere without producing undesirable high concentrations at fresh air intakes, operable doors and windows, and locations on or near the building where access is uncontrolled. Three primary factors that influence the proper disposal of effluent gases are stack/intake separation, stack height, and stack height plus momentum. Chapter 16 of the 2001 *ASHRAE Handbook—Fundamentals* covers the criteria and formulas to calculate the effects of these physical relationships. For complex buildings or buildings with unique terrain or other obstacles to the airflow around the building, either scale model wind tunnel testing or computational fluid dynamics should be considered. However, standard k-ε computational fluid dynamics methods as applied to airflow around buildings need further development (Murakami et al. 1996; Zhou and Stathopoulos 1996).

Stack/Intake Separation

Separation of the stack discharge and air intake locations allows the atmosphere to dilute the effluent. Separation is simple to calculate with the use of short to medium-height stacks; however, to achieve adequate atmospheric dilution of the effluent, greater separation than is physically possible may be required, and the building roof near the stack will be exposed to higher concentrations of the effluent.

Stack Height

Chapter 15 of the 1997 *ASHRAE Handbook—Fundamentals* describes a geometric method to determine the stack discharge height high enough above the turbulent zone around the building that little or no effluent gas impinges on air intakes of the emitting building. The technique is conservative and generally requires tall stacks that may be visually unacceptable or fail to meet building code or zoning requirements. Also, the technique does not ensure acceptably low concentrations of effluents at air intakes (e.g., if there are large releases of hazardous materials or elevated intake locations on nearby buildings). A minimum stack height of 10 ft is required by AIHA *Standard* Z9.5 and is recommended by Appendix A of NFPA *Standard* 45.

Stack Height plus Momentum

To increase the effective height of the exhaust stacks, both the volumetric flow and the discharge velocity can be increased to increase the discharge momentum (Momentum Flow = Density × Volumetric Flow × Velocity). The momentum of the large vertical flow in the emergent jet lifts the plume a substantial distance above the stack top, thereby reducing the physical height of the stack and making it easier to screen from view. This technique is particularly suitable when (1) many small exhaust streams can be clustered together or manifolded prior to the exhaust fan to provide the large volumetric flow and (2) outside air can be added through automatically controlled dampers to provide constant exhaust velocity under variable load. The drawbacks to the second arrangement are the amount of energy consumed to achieve the constant high velocity and the added complexity of the controls to maintain constant flow rates. Dilution equations presented in Chapter 16 of the 2001 *ASHRAE Handbook—Fundamentals* or mathematical plume analysis (e.g., Halitsky 1989) can be used to predict the performance of this arrangement, or performance can be validated through wind tunnel testing. Current mathematical procedures tend to have a high degree of uncertainty, and the results should be judged accordingly.

Architectural Screens

Rooftop architectural screens around exhaust stacks are known to adversely affect exhaust dispersion. In general, air intakes should not be placed within the same screen enclosure as laboratory exhausts. Petersen et al. (1997) describe a method of adjusting dilution predictions of Chapter 16 of the 2001 *ASHRAE Handbook—Fundamentals* using a stack height adjustment factor, which is essentially a function of screen porosity.

Criteria for Suitable Dilution

An example criterion based on Halitsky (1988) is that the release of 15 cfm of pure gas through any stack in a moderate wind (3 to

18 mph) from any direction with a near-neutral atmospheric stability (Pasquill Gifford Class C or D) must not produce concentrations exceeding 3 ppm at any air intake. This criterion is meant to simulate an accidental release such as would occur in a spill of an evaporating liquid or after the fracture of the neck of a small lecture bottle of gas in a fume hood.

The intent of this criterion is to limit the concentration of exhausted gases at the air intake locations to levels below the odor thresholds of gases released in fume hoods, excluding highly odorous gases such as mercaptans. Laboratories that use extremely hazardous substances should conduct a chemical-specific analysis based on published health limits. A more lenient limit may be justified for laboratories with low levels of chemical usage. Project-specific requirements must be developed in consultation with the safety officer. The equations in Chapter 16 of the 2001 *ASHRAE Handbook—Fundamentals* are presented in terms of dilution, defined as the ratio of stack exit concentration to receptor concentration. The exit concentration, and therefore the dilution required to meet the criterion, varies with the total volumetric flow rate of the exhaust stack. For the above criterion with the emission of 15 cfm of a pure gas, a small stack with a total flow rate of 1000 cfm will have an exit concentration of 15/1000 or 15,000 ppm. A dilution of 1:5000 is needed to achieve an intake concentration of 3 ppm. A larger stack with a flow rate of 10,000 cfm will have a lower exit concentration of 15/10,000 or 1500 ppm and would need a dilution of only 1:500 to achieve the 3 ppm intake concentration.

The above criterion is preferred over a simple dilution standard because a defined release scenario (15 cfm) is related to a defined intake concentration (3 ppm) based on odor thresholds or health limits. A simple dilution requirement may not yield safe intake concentrations for a stack with a low flow rate.

Adjacent Building Effects

The influence of adjacent building effects was studied under ASHRAE *Research Project* 897 (Wilson et al. 1998). Several guidelines were developed from this project:

- Designers should locate stacks near the edge of a roof.
- With the emitting building upwind, an adjacent building will always have higher dilution on a lower step-down roof than would occur on a flat roof at the emitting building's height. Ignoring the step-down in roof level will produce conservative designs.
- If the lower adjacent building is upwind of the emitting building, it will block flow approaching the emitting building, producing lower velocities and recirculation cavities on the emitting building roof and increasing dilution by factors of 2 to 10 on the emitting building.
- Designers should use increased exhaust velocity to produce jet dilution when the plume will be trapped in the recirculation cavity from a high upwind adjacent building.
- When the adjacent building is higher than the emitting building, designers should try to avoid placing air intakes on the adjacent building at heights above the roof level of the emitting building.

Also see Chapter 44, Building Air Intake and Exhaust Design, for more information.

APPLICATIONS

LABORATORY ANIMAL FACILITIES

Laboratory animals must be housed in comfortable, clean, temperature- and humidity-controlled rooms. Animal welfare must be considered in the design; the air-conditioning system must provide the macroenvironment for the animal room and the subsequent effect on the microenvironment in the animal's primary enclosure or cage specified by the facility's veterinarian (Besch 1975; ILAR 1996; Woods 1980). Early detailed discussions with the veterinarian concerning airflow patterns, cage layout, and risk assessment help ensure a successful animal room HVAC design. The elimination of research variables (fluctuating temperature and humidity, drafts, and spread of airborne diseases) is another reason for a high-quality air-conditioning system. See Chapter 22 for additional information on environments for laboratory animals.

Primary Uses of Animal Housing Facilities

Primary uses of animal facilities include the following:

- **Acute (short-term) studies:** generally less than 90 days in length, although the animal species and particular experiments involved could affect duration. Most frequently found in pharmaceutical, medical, or other life science laboratories, and includes
  - Assays and screens
  - Immune-suppressed animals
  - Pharmacology and metabolism
  - Infectious disease
- **Chronic (long-term) studies:** generally more than 90 days in length, although the species and experiment involved could affect the length. Includes
  - Toxicology
  - Teratology
  - Neurological
  - Quality control
- **Long-term holding of animals,** including
  - Production of materials used primarily in pharmaceuticals
  - Breeding
  - Laboratory animals
  - Companion animals
  - Food and fiber animals
- **Agricultural studies,** including food and fiber animals

Regulatory Environment

There are a number of regulations and guidelines that pertain to the housing of laboratory animals. Additional regulations cover the housing of animals that may be used some way in the production of pharmaceuticals, testing for agricultural products or used for quality control. The pertinent regulations are outlined below and are applied in the United States. Other countries have similar regulations that should be consulted when designing animal facilities located in that respective country. The regulations and guidelines include the following:

- Code of Federal Regulations (CFR) 21
  Part 58; Good Laboratory Practices for Non-Clinical Laboratory Studies
  Part 210; current Good Manufacturing Practice in Manufacture, Processing, Packing or Holding of Human and Veterinary Drugs
- Guide for the Care and Use of Laboratory Animals, National Research Council
- Biosafety in Microbiological and Biomedical Laboratories, Center for Disease Control (CDC).
- The Animal Welfare Act of 1966 and as subsequently amended. Regulatory authority is vested in the Secretary of the U.S. Department of Agriculture (USDA) and implemented by the USDA's Animal and Plant Health Inspection Service.
- American Association for Accreditation of Laboratory Animal Care (AAALAC), a nonprofit organization to which many institutions and corporations belong. This group provides accreditation based upon inspections and reports from member groups. Many organizations that build or maintain animal facilities adhere to AAALAC programs and HVAC engineers are expected to design to their guidelines.

Local ordinances or user organization requirements may also apply. HVAC engineers should confirm which regulations are applicable for any project.

Temperature and Humidity

Due to the nature of research programs, air-conditioning design temperature and humidity control points may be required. Research animal facilities require more precise environmental control than farm animal or production facilities because variations affect the experimental results. A totally flexible system permits control of the temperature of individual rooms to within ±2°F for any set point in a range of 64 to 85°F. This flexibility requires significant capital expenditure, which can be mitigated by designing the facility for selected species and their specific requirements.

Table 1 lists dry-bulb temperatures recommended by ILAR (1996) for several common species. In the case of animals in confined spaces, the range of daily temperature fluctuations should be kept to a minimum. Relative humidity should also be controlled. ASHRAE *Standard* 62 recommends that the relative humidity in habitable spaces be maintained between 30 and 60% to minimize growth of pathogenic organisms. ILAR (1996) suggests the acceptable range of relative humidity is 30 to 70%.

Ventilation

A guideline of 10 to 15 outside air changes per hour (ACH) has been used for secondary enclosures for many years. Although it is effective in many settings, the guideline does not consider the range of possible heat loads; the species, size, and number of animals involved; the type of bedding or frequency of cage changing; the room dimensions; or the efficiency of air distribution from the secondary to the primary enclosure. In some situations, such a flow rate might overventilate a secondary enclosure that contains few animals and waste energy or underventilate a secondary enclosure that contains many animals and allow heat and odor to accumulate.

For small-animal caging systems, recent studies suggest that room conditions have very little influence on the cage environments. ASHRAE *Research Project* RP-730 (Riskowski et al. 1995, 1996) found the following:

- No relationship between room ventilation rate and cage microenvironments for shoebox and microisolator cages exists. In fact, 5 ACH provided the same cage ventilation rates for shoebox cages as did 10 and 15 ACH.
- Diffuser type (perforated square versus radial) had only a small effect on shoebox cage ventilation rates. The radial diffuser provided higher wire cage ventilation rates.
- One high return provided the same cage ventilation rates as four high returns or as one low return.
- Room size had no effect on cage ventilation rates.

This research is further discussed in Chapter 22.

In certain types of animal rooms, usually those used for long-term studies involving high-value work or animals, the outside air change rate is maintained at the 10 to 15 per hour but the total airflow in the rooms ranges from 90 to 150 ACH (mass flow spaces similar to clean rooms). The air supply is generally terminal-HEPA-filtered to reduce the potential for disease. These rooms are energy-intensive, and may not be required with the filter capability and caging systems available today.

The air-conditioning load and flow rate for an animal room should be determined by the following factors:

- Desired animal microenvironment (Besch 1975, 1980; ILAR 1996)
- Species of animal(s)
- Animal population
- Recommended ambient temperature (Table 1)
- Heat produced by motors on special animal housing units (e.g., laminar flow racks or HEPA-filtered air supply units for ventilated racks)
- Heat generated by the animals (Table 2)

Additional design factors include method of animal cage ventilation; operational use of a fume hood or a biological safety cabinet during procedures such as animal cage cleaning and animal examination; airborne contaminants (generated by animals, bedding, cage cleaning, and room cleaning); and institutional animal care standards (Besch 1980, ILAR 1996). It should be noted that the ambient conditions of the animal room might not reflect the actual conditions within a specific animal cage.

Table 1 Recommended Dry-Bulb Temperatures for Common Laboratory Animals

Animal	Temperature, °F
Mouse, rat, hamster, gerbil, guinea pig	64 to 79
Rabbit	61 to 72
Cat, dog, nonhuman primate	64 to 84
Farm animals and poultry	61 to 81

Source: ILAR (1996).
Note: These ranges permit scientific personnel who will use the facility to select optimum conditions (set points). The ranges do not represent acceptable fluctuation ranges.

Animal Heat Production

Air-conditioning systems must remove the sensible and latent heat produced by laboratory animals. The literature concerning the metabolic heat production appears to be divergent, but new data are consistent. Current recommended values are given in Table 2. These values are based on experimental results and the following equation:

$$\mathrm{ATHG} = 2.5M$$

where

ATHG = average total heat gain, Btu/h per animal
M = metabolic rate of animal, Btu/h per animal = $6.6W^{0.75}$
W = weight of animal, lb

Conditions in animal rooms must be maintained constant. This may require year-round availability of refrigeration and, in some cases, dual/standby chillers and emergency electrical power for motors and control instrumentation. Storage of critical spare parts is one alternative to installing a standby refrigeration system.

Design Considerations

If the entire animal facility or extensive portions of it are permanently planned for species with similar requirements, the range of

Table 2 Heat Generated by Laboratory Animals

Species	Weight, lb	Heat Generation, Btu/h per Normally Active Animal		
		Sensible	Latent	Total
Mouse	0.046	1.11	0.54	1.65
Hamster	0.260	4.02	1.98	6.00
Rat	0.62	7.77	3.83	11.6
Guinea pig	0.90	10.2	5.03	15.2
Rabbit	5.41	39.2	19.3	58.5
Cat	6.61	45.6	22.5	68.1
Nonhuman primate	12.0	71.3	35.1	106.0
Dog	22.7	105.0	56.4	161.0
Dog	50.0	231.0	124.0	355.0

individual adjustments may be reduced. Each animal room or group of rooms serving a common purpose should have separate temperature and humidity controls. The animal facility and human occupancy areas should be conditioned separately. The human areas may use a return air HVAC system and may be shut down on weekends for energy conservation. Separation prevents exposure of personnel to biological agents, allergens, and odors from animal rooms.

Control of air pressure in animal housing and service areas is important to ensure directional airflow. For example, quarantine, isolation, soiled equipment, and biohazard areas should be kept under negative pressure, whereas clean equipment and pathogen-free animal housing areas and research animal laboratories should be kept under positive pressure (ILAR 1996).

Supply air outlets should not cause drafts on research animals. Efficient air distribution for animal rooms is essential; this may be accomplished effectively by supplying air through ceiling outlets and exhausting air at floor level (Hessler and Moreland 1984). Supply and exhaust systems should be sized to minimize noise.

A study by Neil and Larsen (1982) showed that predesign evaluation of a full-size mock-up of the animal room and its HVAC system was a cost-effective way to select a system that distributes air to all areas of the animal-holding room. Wier (1983) describes many typical design problems and their resolutions. Room air distribution should be evaluated using ASHRAE *Standard* 113 procedures to evaluate drafts and temperature gradients.

HVAC ductwork and utility penetrations must present a minimum number of cracks in animal rooms so that all wall and ceiling surfaces can be easily cleaned. Exposed ductwork is not generally recommended; however, if constructed of 316 stainless steel in a fashion to facilitate removal for cleaning, it can provide a cost-effective alternative. Joints around diffusers, grilles, and the like should be sealed. Exhaust air grilles with 1 in. washable or disposable filters are normally used to prevent animal hair and dander from entering the ductwork. Noise from the HVAC system and sound transmission from nearby spaces should be evaluated. Sound control methods such as separate air-handling systems or sound traps should be used as required.

Multiple-cubicle animal rooms enhance the operational flexibility of the animal room (i.e., housing multiple species in the same room, quarantine, and isolation). Each cubicle should be treated as if it were a separate animal room, with air exchange/balance, temperature, and humidity control.

Caging Systems

Animal facilities use a number of different caging systems that can significantly affect the environment within the cage or the total heat load in the room. The purpose of the caging systems is to

- Protect the health and wellbeing of the animals
- Protect support staff from antigens released or shed by the animals
- Minimize exposure of animals to pheromones released by other animals in the space

To provide the appropriate design, the HVAC engineer must be aware of the type of caging system to be used. Some common caging systems include the following:

- Cage boxes made of sheet metal, plastic, or wire mesh, with the space inside the cage open to the room so that the room's macroenvironment is essentially identical to the cage's microenvironment.
- Cage boxes made primarily of plastic, with the top shielded from the room by a filter material to provide some level of isolation from the room. The filter is usually not sealed to the cage, so some open space between the room and the interior of the cage remains. Exchange of air, vapors, particulates, and gases between the room and the cage interior does occur, but the rate of exchange is reduced by the filter. The microenvironment of the interior of the cage is usually different from that of the room.
- Plastic and wire cages that are part of a cage rack assembly, which provides varying degrees of isolation from the room. These usually provide filtered (generally HEPA-filtered) air directly to each individual or shelf of cage boxes. In some cases, both a fan-powered supply and an exhaust unit are used. In other cases, cage units are connected to the facility exhaust system to provide airflow. Facilities with this kind of caging system must be designed to accommodate the heat gain in the space if the exhaust is released in the room. Some heat gain may be excluded if the caging assembly is connected directly to the facility exhaust system. When the facility is used to provide the exhaust by direct connection to the caging assembly, the design must include provisions to control the airflow to ensure that the overall proper airflow and relative static pressure of the room and each cage rack assembly is maintained, especially when caging and rack connections may be changed over time. The temperature and specific humidity within each cage will be higher then the ambient conditions of the room.

ANCILLARY SPACES FOR ANIMAL LABORATORIES

In addition to animal holding rooms, a facility intended to provide for an animal colony generally requires other areas, such as

- **Cage washer:** Usually provided with some temperature control to minimize heat stress for occupants. In addition, specific exhaust hoods and separate exhaust ductwork should be considered for the space and equipment.
- **Feed storage:** Usually provided with temperature and humidity control to protect quality and shelf life of feed.
- **Diagnostic laboratory:** Usually provided with laboratory-quality air conditioning.
- **Treatment laboratory:** Usually provided with laboratory-quality air conditioning.
- **Quarantine spaces:** To separate incoming animals from the remainder of the colony until their health can be evaluated. These rooms are frequently located near the receiving location. Animal-room-quality air conditioning is provided.
- **Surgery suite:** Sterile-quality air conditioning is provided. The suites frequently have provisions to exhaust anesthetic gases.
- **Necropsy laboratory:** Usually provided with laboratory-quality air conditioning and frequently fitted with special exhaust tables or other means of protecting laboratory workers from exposure to chemical preservatives or biological contamination. For high-risk or high-hazard work, Type III biological safety cabinets may be provided.
- **Waste-holding room:** Usually only provided with heating and ventilation, but maintained at negative pressure relative to adjacent areas. When used to store carcasses, a refrigerated storage unit of appropriate size should be provided.

CONTAINMENT LABORATORIES

With the initiation of biomedical research involving recombinant DNA technology, federal guidelines on laboratory safety were published that influence design teams, researchers, and others. Containment describes safe methods for managing hazardous chemicals and infectious agents in laboratories. The three elements of containment are laboratory operational practices and procedures, safety equipment, and facility design. Thus, the HVAC design engineer helps decide two of the three containment elements during the design phase.

In the United States, the U.S. Department of Health and Human Services (DHHS), Centers for Disease Control and Prevention (CDC), and National Institutes of Health (NIH) classify biological laboratories into four levels—Biosafety Levels 1 through 4—listed in DHHS (1999).

Biosafety Level 1

Biosafety Level 1 is suitable for work involving agents of no known hazard or of minimal potential hazard to laboratory personnel and the environment. The laboratory is not required to be separated from the general traffic patterns in the building. Work may be conducted either on an open benchtop or in a chemical fume hood. Special containment equipment is neither required nor generally used. The laboratory can be cleaned easily and contains a sink for washing hands. The federal guidelines for these laboratories contain no specific HVAC requirements, and typical college laboratories are usually acceptable. Many colleges and research institutions require directional airflow from the corridor into the laboratory, chemical fume hoods, and approximately three to four air changes per hour of outside air. Directional airflow from the corridor into the laboratory helps to control odors.

Biosafety Level 2

Biosafety Level 2 is suitable for work involving agents of moderate potential hazard to personnel and the environment. DHHS (1999) contains lists that explain the levels of containment needed for various hazardous agents. Laboratory access is limited when certain work is in progress. The laboratory can be cleaned easily and contains a sink for washing hands. Biological safety cabinets (Class I or II) are used whenever

- Procedures with a high potential for creating infectious aerosols are conducted. These include centrifuging, grinding, blending, vigorous shaking or mixing, sonic disruption, opening containers of infectious materials, inoculating animals intranasally, and harvesting infected tissues or fluids from animals or eggs.
- High concentrations or large volumes of infectious agents are used. Federal guidelines for these laboratories contain minimum facility standards.

At this level of biohazard, most research institutions have a full-time safety officer (or safety committee) who establishes facility standards. The federal guidelines for Biosafety Level 2 contain no specific HVAC requirements; however, typical HVAC design criteria can include the following:

- 100% outside air systems
- 6 to 15 air changes per hour
- Directional airflow into the laboratory rooms
- Site-specified hood face velocity at fume hoods (many institutions specify 80 to 100 fpm)
- An assessment of research equipment heat load in a room.
- Inclusion of biological safety cabinets

Most biomedical research laboratories are designed for Biosafety Level 2. However, the laboratory director must evaluate the risks and determine the correct containment level before design begins.

Biosafety Level 3

Biosafety Level 3 applies to facilities in which work is done with indigenous or exotic agents that may cause serious or potentially lethal disease as a result of exposure by inhalation. The Biosafety Level 3 laboratory uses a physical barrier of two sets of self-closing doors to separate the laboratory work area from areas with unrestricted personnel access. This barrier enhances biological containment to within the laboratory work area.

The ventilation system must be single-pass, nonrecirculating and configured to maintain the laboratory at a negative pressure relative to surrounding areas. Audible alarms and visual monitoring devices are recommended to notify personnel if the laboratory pressure relationship changes from a negative to a positive condition. The user may wish to have alarms reported to a remote constantly monitored location. Gastight dampers are required in the supply and exhaust ductwork to allow decontamination of the laboratory. The ductwork between these dampers and the laboratory must also be gastight. All penetrations of the Biosafety Level 3 laboratory envelope must be sealed for containment and to facilitate gaseous decontamination of the work area.

All procedures involving the manipulation of infectious materials are conducted inside biological safety cabinets. The engineer must ensure that the connection of the cabinets to the exhaust system does not adversely affect the performance of the biological safety cabinets or the exhaust system. Refer to the section on Biological Safety Cabinets for further discussion.

The exhaust air from biological safety cabinets and/or the laboratory work area may require HEPA filtration. The need for filtration should be reviewed with the appropriate safety officers. If required, HEPA filters should be equipped with provisions for bag-in, bag-out filter handling systems and gastight isolation dampers for biological decontamination of the filters.

The engineer should review with the safety officer the need for special exhaust or filtration of exhaust from any scientific equipment located in the Biosafety Level 3 laboratory.

Biosafety Level 4

Biosafety Level 4 is required for work with dangerous and exotic agents that pose a high risk of aerosol-transmitted laboratory infections and life-threatening disease. HVAC systems for these areas will have stringent design requirements that must be determined by the biological safety officer.

SCALE-UP LABORATORIES

Scale-up laboratories are defined differently depending on the nature and volume of work being conducted. For laboratories performing recombinant DNA research, large-scale experiments involve 10 L or more. A chemical or biological laboratory is defined as scale-up when the principal holding vessels are glass or ceramic. When the vessels are constructed primarily of metals, the laboratory is considered a pilot plant, which this chapter does not address. The amount of experimental materials present in scale-up laboratories is generally significantly greater than the amount found in the small-scale laboratory. Experimental equipment is also larger and therefore requires more space; these may include larger chemical fume hoods or reaction cubicles that may be of the walk-in type. Significantly higher laboratory airflow rates are needed to maintain the face velocity of the chemical fume hoods or reaction cubicles, although their size frequently presents problems of airflow uniformity over the entire face area. Walk-in hoods are sometimes entered during an experimental run, so provisions for breathing-quality air stations and other forms of personnel protection should be considered. Environmental containment or the ability to decontaminate the laboratory, the laboratory exhaust airstream, or other effluent may be needed in the event of an upset. Scale-up laboratories may be in operation for sustained periods.

For large walk-in hoods or reaction cubicles, the large volume of exhaust air required and the simultaneous requirement for supply air can result in temperature gradient problems in the space. Local specific ventilation capability is frequently provided within the laboratory space but outside the fume hood or reaction cubicle.

Large hoods, similar to what sometimes were called “California hoods,” may also be provided in scale-up laboratories. These hoods are large in volume and height, provide access on multiple sides, and can be customized using standard components. Before beginning any custom hood design, the HVAC engineer, working with the user, should first determine how the hood will be used. Then the HVAC engineer can develop a custom hood design that considers

- What access is required for setup of experimental apparatus
- How the hood is expected to function during experimental runs
- Which doors or sashes should be open during a run
- Safety and ergonomic issues
- What features should be incorporated

- Airflow required to achieve satisfactory containment

Testing and balancing criteria should also be defined early in the design process. Mockups and factory testing of prototypes should be considered to avoid problems with installed hoods.

TEACHING LABORATORIES

Laboratories in academic settings can generally be classified as either those used for instruction or those used for research. Research laboratories vary significantly depending on the work being performed; they generally fit into one of the categories of laboratories described previously.

The design requirements for teaching laboratories also vary based on their function. The designer should become familiar with the specific teaching program, so that a suitable hazard assessment can be made. For example, the requirements for the number and size of fume hoods vary greatly between undergraduate inorganic and graduate organic chemistry teaching laboratories. Unique aspects of teaching laboratories include the need of the instructor to be in visual contact with the students at their work stations and to have ready access to the controls for the fume hood operations and any safety shutoff devices and alarms. Frequently, students have not received extensive safety instruction, so easily understood controls and labeling are necessary. Because the teaching environment depends on verbal communication, sound from the building ventilation system is an important concern.

CLINICAL LABORATORIES

Clinical laboratories are found in hospitals and as stand-alone operations. The work in these laboratories generally consists of handling human specimens (blood, urine, etc.) and using chemical reagents for analysis. Some samples may be infectious; because it is impossible to know which samples may be contaminated, good work practices require that all be handled as biohazardous materials. The primary protection of the staff at clinical laboratories depends on the techniques and laboratory equipment (e.g., biological safety cabinets) used to control aerosols, spills, or other inadvertent releases of samples and reagents. People outside the laboratory must also be protected.

The building HVAC system can provide additional protection with suitable exhaust, ventilation, and filtration. The HVAC engineer is responsible for providing an HVAC system that meets the biological and chemical safety requirements. The engineer should consult with appropriate senior staff and safety professionals to ascertain what potentially hazardous chemical or biohazardous conditions will be in the facility and then provide suitable engineering controls to minimize risks to staff and the community. Appropriate laboratory staff and the design engineer should consider using biological safety cabinets, chemical fume hoods, and other specific exhaust systems.

RADIOCHEMISTRY LABORATORIES

In the United States, laboratories located in Department of Energy (DOE) facilities are governed by DOE regulations. All other laboratories using radioactive materials are governed by the Nuclear Regulatory Commission (NRC), state, and local regulations. Other agencies may be responsible for the regulation of other toxic and carcinogenic materials present in the facility. Laboratory containment equipment for nuclear processing facilities are treated as primary, secondary, or tertiary containment zones, depending on the level of radioactivity anticipated for the area and the materials to be handled. Chapter 26 has additional information on nuclear laboratories.

OPERATION AND MAINTENANCE

During long-term research studies, laboratories may need to maintain design performance conditions with no interruptions for long periods. Even when research needs are not so demanding, systems that maintain air balance, temperature, and humidity in laboratories must be highly reliable, with a minimal amount of downtime. The designer should work with operation and maintenance personnel as well as users early in the design of systems to gain their input and agreement.

System components must be of adequate quality to achieve reliable HVAC operation, and they should be reasonably accessible for maintenance. Laboratory work surfaces should be protected from possible leakage of coils, pipes, and humidifiers. Changeout of supply and exhaust filters should require minimum downtime.

Centralized monitoring of laboratory variables (e.g., pressure differentials, face velocity of fume hoods, supply flows, and exhaust flows) is useful for predictive maintenance of equipment and for ensuring safe conditions. For their safety, laboratory users should be instructed in the proper use of laboratory fume hoods, safety cabinets, ventilated enclosures, and local ventilation devices. They should be trained to understand the operation of the devices and the indicators and alarms that show whether they are safe to operate. Users should request periodic testing of the devices to ensure that they and the connected ventilation systems are operating properly.

Personnel who know the nature of the contaminants in a particular laboratory should be responsible for decontamination of equipment and ductwork before they are turned over to maintenance personnel for work.

Maintenance personnel should be trained to keep laboratory systems in good operating order and should understand the critical safety requirements of those systems. Preventive maintenance of equipment and periodic checks of air balance should be scheduled. High-maintenance items should be placed outside the actual laboratory (in service corridors or interstitial space) to reduce disruption of laboratory operations and exposure of the maintenance staff to laboratory hazards. Maintenance personnel must be aware of and trained in procedures for maintaining good indoor air quality (IAQ) in laboratories. Many IAQ problems have been traced to poor maintenance due to poor accessibility (Woods et al. 1987).

ENERGY

Because of the nature of the functions they support, laboratory HVAC systems consume large amounts of energy (high flow rates; high static pressure filtration; critical cooling, heating, and humidification). Efforts to reduce energy use must not compromise standards established by safety officers. Typically, HVAC systems supporting laboratories and animal areas use 100% outside air and operate continuously. All HVAC systems serving laboratories can benefit from energy reduction techniques that are either an integral part of the original design or added later. Energy reduction techniques should be analyzed in terms of both appropriateness to the facility and economic payback.

Energy-efficient design is an iterative process that begins with establishing communication among all members of the design team. Each design discipline has an effect on the energy load. On a macro scale, the flexibility of the architectural design can allow such features as a modular laboratory size. On a micro scale, the choice of a lighting system can affect sensible heat gain and transformer sizing, for example. Energy-efficient designs account for the potential variability of a minimized load and match the load with flexible electrical and mechanical systems. This systems approach is fundamental to an integrated system design.

The HVAC engineer must understand and respond to the scientific requirements of the facility. Research requirements typically include continuous control of temperature, humidity, relative static pressure, and air quality. Energy reduction systems must maintain

required environmental conditions during both occupied and unoccupied modes.

Energy Efficiency

Energy can be used more efficiently in laboratories by reducing exhaust air requirements. One way to achieve this is to use variable-volume control of exhaust air through the fume hoods to reduce exhaust airflow when the fume hood sash is not fully open. Any airflow control must be integrated with the laboratory control system, described in the section on Control, and must not jeopardize the safety and function of the laboratory.

Another energy-efficiency method uses night setback controls when the laboratory is unoccupied to reduce exhaust volume to one-quarter to one-half the minimum required when the laboratory is occupied. Timing devices, sensors, manual override, or a combination of these can be used to set back the controls at night. If this strategy is a possibility, the safety and function of the laboratory must be considered, and appropriate safety officers should be consulted.

Also, fume sash configurations that limit the opening to less than the full open condition should be considered.

Energy Recovery

Energy can often be recovered economically from the exhaust airstream in laboratory buildings with large quantities of exhaust air. Many energy recovery systems are available, including rotary air-to-air energy exchangers or heat wheels, coil energy recovery loops (runaround cycle), twin tower enthalpy recovery loops, heat pipe heat exchangers, fixed-plate heat exchangers, thermosiphon heat exchangers, and direct evaporative cooling. Some of these technologies can be combined with indirect evaporative cooling for further energy recovery. See Chapter 44 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment* for more information.

Concerns about the use of energy recovery devices in laboratory HVAC systems include (1) the potential for cross-contamination of chemical and biological materials from exhaust air to the intake airstream, and (2) the potential for corrosion and fouling of devices located in the exhaust airstream. NFPA *Standard* 45 specifically prohibits the use of latent heat recovery devices in fume hood exhaust systems.

Energy recovery is also possible for hydronic systems associated with HVAC. Rejected heat from centrifugal chillers can be used to produce low-temperature reheat water. Potential also exists in plumbing systems, where waste heat from washing operations can be recovered to heat makeup water.

COMMISSIONING

In addition to HVAC systems, electrical systems and chemical handling and storage areas must be commissioned. Training of technicians, scientists, and maintenance personnel is a critical aspect of the commissioning process. Users must understand the systems and their operation.

It should be determined early in the design process whether any laboratory systems must comply with Food and Drug Administration (FDA) regulations because these systems have additional design and commissioning requirements. Commissioning is defined in Chapter 42, and the process is outlined in ASHRAE *Guideline* 1. Laboratory commissioning is more demanding than that described in ASHRAE *Guideline* 1 because areas must be considered that are not associated with the normal office complex. Requirements for commissioning should be clearly understood by all participants, including the contractors and the owner's personnel. Roles and responsibilities should be defined, and responsibilities for documenting results should be established.

Laboratory commissioning starts with the intended use of the laboratory and should include development of a commissioning plan, as outlined in ASHRAE *Guideline* 1. The validation of individual components should come first; after individual components are successfully validated, the entire system should be evaluated. This requires verification and documentation that the design meets applicable codes and standards and that it has been constructed in accordance with the design intent. Before general commissioning begins, the following data must be obtained:

- Complete set of the laboratory utility drawings
- Definition of the use of the laboratory and an understanding of the work being performed
- Equipment requirements
- All test results
- Understanding of the intent of the system operation

For HVAC system commissioning, the following should be verified and documented:

- Fume hood design face velocities have been met.
- Manufacturer's requirements for airflow for biological safety cabinets and laminar flow clean benches have been met.
- Exhaust system configuration, damper locations, and performance characteristics, including any required emission equipment, are correct.
- Control system operates as specified. Controls include fume hood alarm; miscellaneous safety alarm systems; fume hood and other exhaust airflow regulation; laboratory pressurization control system; laboratory temperature control system; and main ventilation unit controls for supply, exhaust, and heat recovery systems. Control system performance verification should include speed of response, accuracy, repeatability, turndown, and stability.
- Desired laboratory pressurization relationships are maintained throughout the laboratory, including entrances, adjoining areas, air locks, interior rooms, and hallways. Balancing terminal devices within 10% of design requirements will not provide adequate results. Additionally, internal pressure relationships can be affected by airflow around the building itself. See Chapter 16 of the 2001 *ASHRAE Handbook—Fundamentals* for more information.
- Fume hood containment performance is within specification. ASHRAE *Standard* 110 provides criteria for this evaluation.
- Dynamic response of the laboratory's control system is satisfactory. One method of testing the control system is to open and shut laboratory doors during fume hood performance testing.
- System fault tree and failure modes are as specified.
- Standby electrical power systems function properly.
- Design noise criterion (NC) levels of occupied spaces have been met.

ECONOMICS

In laboratories, HVAC systems make up a significant part (often 30 to 50%) of the overall construction budget. The design criteria and system requirements must be reconciled with the budget allotment for HVAC early in the planning stages and continually throughout the design stages to ensure that the project remains within budget.

Every project must be evaluated on both its technical features and its economics. The following common economic terms are discussed in Chapter 36 and defined here as follows:

Initial cost: Costs to design, install, and test an HVAC system such that it is fully operational and suitable for use.

Operating cost: Cost to operate a system (including energy, maintenance, and component replacements) such that the total system can reach the end of its normal useful life.

Life-cycle cost: Cost related to the total cost over the life of the HVAC system, including initial capital cost, considering the time value of money.

Mechanical and electrical costs related to HVAC systems are commonly assigned a depreciation life based on current tax policies. This depreciation life may be different from the projected functional life of the equipment, which is influenced by the quality of the system components and of the maintenance they receive. Some portions of the system, such as ductwork, could last the full life of the building. Other components, such as air-handling units, may have a useful life of 15 to 30 years, depending on their original quality and ongoing maintenance efforts. Estimated service life of equipment is listed in Chapter 36.

Engineering economics can be used to evaluate life-cycle costs of configuration (utility corridor versus interstitial space), systems, and major equipment. The user or owner makes a business decision concerning the quality and reliability of the system and its ongoing operating costs. The HVAC engineer may be asked to provide an objective analysis of energy, maintenance, and construction costs, so that an appropriate life-cycle cost analysis can be made. Other considerations that may be appropriate include economic influences related to the long-term use of energy and governmental laws and regulations.

Many technical considerations and the great variety of equipment available influence the design of HVAC systems. Factors affecting design must be well understood to ensure appropriate comparisons between various systems and to determine the impact on either first or operating costs.

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