Designing Your New Animal Facility Part II: Integration of Engineering Controls in Animal Facility Design

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The purpose of using animals in research, testing, or education is the production of valid data. For this reason, animal facilities must be designed, maintained, and operated to provide optimal environmental conditions and to prevent variations in the animals' environment while ensuring the best practices of humane care, use, and management of laboratory animals.

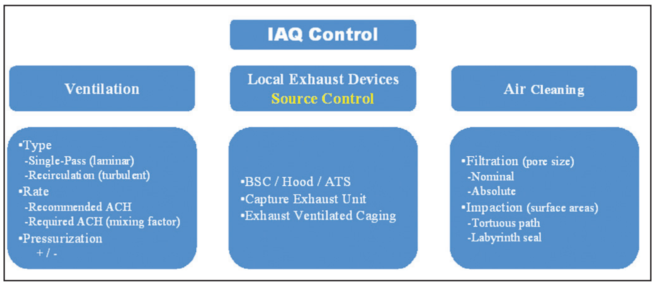
Environmental stressors, animal disturbances, and environmental factors can affect an animal's environmental stability and induce experimental variables. Stressors can include noise, vibration, population density, physical activity, social interaction, bedding, nesting, and enrichment structures and devices. Disturbances are often from human contact, such as researcher observations or cage intrusions for health check, watering, feeding, cage changing, and animal handling. Additionally, animals can be affected by changes in the moods of the people with whom they have contact. Environmental factors include feed, water, light (quality, quantity, and cycle), and indoor air quality (IAQ). IAQ consists of ambient temperature (T), relative humidity (RH), air composition (oxygen, waste gases, odors, particulates), and air velocity, change rate, pressurization, makeup, and mixing. IAQ has a direct effect on an animal's health and well-being by influencing environmental stability. A lack of environmental stability can induce behavioral and physiological changes in experimental animals that could confound data (1).

In order to prevent negative effects of air quality on experimental animals, engineering controls to safeguard species-specific IAQ should be used. For instance, an HVAC (heating, ventilation, and air conditioning) system and/or a ventilated caging system may be used to control, optimize, and maintain room and cage IAQ, respectively.

According to some references, cost-effective engineering controls should be used to provide for environmental stability and to ensure the health, safety, comfort, and well-being of the animals and staff (2,3,4,5). Therefore, it is important to establish IAQ standards that optimize stable environmental conditions and minimize experimental variables. There are three engineering controls commonly used to achieve IAQ standards for rooms and cages: ventilation; local exhaust devices (LED), also called source control; and air cleaning systems (5,6). These controls are described below and summarized in Table 1.

Ventilation

To achieve optimum IAQ at room and cage levels, ventilation systems must supply adequate oxygen, T, and RH; remove airborne contaminants such as odors, allergens, particles, and waste gases; avoid accumulations (buildup) of heat load and moisture; and provide comfortable, optimal, and stable environmental conditions. There are two types of ventilation—single-pass and recirculation airflow.



IAQ Control		
Ventilation	Local Exhaust Devices Source Control	Air Cleaning
•Type -Single-Pass (laminar) -Recirculation (turbulent) •Rate -Recommended ACH -Required ACH (mixing factor) •Pressurization + / -	•BSC / Hood / ATS •Capture Exhaust Unit •Exhaust Ventilated Caging	•Filtration (pore size) -Nominal -Absolute •Impaction (surface areas) -Tortuous path -Labyrinth seal

Table 1.

Single-pass or laminar airflow ventilation is where 100% of air supplied to an area is exhausted to the outside. This type of ventilation is the most efficient way to control, optimize, and maintain IAQ (5). It is the ventilation of choice for safety equipment, such as biosafety cabinets (BSC) and in the microelectronics industry where Class 10 to 100,000 cleanroom facilities are designed to eliminate airborne contaminants from the work surface area. Construction and maintenance of such facilities are very costly and the operation of such facilities can be difficult to manage. Nevertheless, there are animal room and cage rack systems with single-pass ventilation designed by veterinarians, HVAC engineers, and computational fluid dynamics (CFD) professionals (7,8). It has been demonstrated that single-pass ventilation supplies fresh air with adequate oxygen, T, and RH; avoids recirculation and accumulation of T, RH, waste gases, and airborne contaminants in the enclosure; and removes contaminated air as it exhausts directly to the outside. Also, single-pass systems protect the caged-animals, the staff, and the environment from airborne contamination; assure IAQ at both room and cage levels; and reduce the operating costs of HVAC and cage ventilation.

Recirculation or dilution-removal ventilation is where all or most of exhausted air continuously returns to the same area. Some fresh air mixes with the portion of air that was not discharged to outside the enclosure. The resulting mixture of contaminated air is recirculated. This type of ventilation is the least efficient in controlling and maintaining IAQ. However, at home, office, and work, recirculating a major portion of warmed or cooled air is considered cheaper and easier to manage than constantly conditioning the whole volume of air in the enclosure. Nevertheless, recirculation ventilation fails to remove or avoid buildup of heat load, moisture, and airborne contaminants; it dilutes them instead. Also, as zones of turbulence and dead-air space are created in the enclosure, dilution-removal ventilation prevents comfortable, optimal, and stable environmental conditions. To improve IAQ for recirculated systems, costly improvements such as increasing ventilation rates, using CFD (computational fluid dynamics) analysis to design enclosures with good air mixing factors (air distribution pattern), and/or using local exhaust devices can be used.

The type of ventilation and air mixing factor define ventilation rate.

- **Rate:** Recommended and required ventilation rates are expressed in ACH (air changes per hour). There are calculation methods and tables to estimate room and cage ACH that would achieve IAQ and airborne contamination control (5).

$$\text{Recommended ACH} = \frac{Q\ [\text{exhaust airflow, ft}^3/\text{min.}] \times 60}{V\ [\text{volume, ft}^3]}$$

The recommended rate of ventilation is the minimal ventilation required to accommodate the heat load expected to be generated by the largest number of animals to be housed plus any heat expected to be produced by non-animal sources and heat transfer through room surfaces (2). A mechanical engineer can determine the recommended ACH (see above) from the average total heat gain formula, as published by ASHRAE (American Society of Heating, Refrigeration, and Air-Conditioning Engineers) and the Total-Cooling-Load Calculation (5,9).

Required ACH = Recommended ACH x Mixing Factor

The required rate (see above) of ventilation depends on the air mixing factor prevailing in the enclosure; i.e., a room or a cage. Adequate air mixing, which requires that an adequate number of ACH be provided to an enclosure, must be ensured to prevent both stagnation and short-circuiting of air; i.e., passage of air directly from the air supply to the air exhaust. However, air rarely changes to the calculated recommended ACH because the airflow patterns in the enclosure may not permit complete mixing of the supply and enclosure air in all parts of the enclosure. To account for this variation, a mixing factor (which ranges from 1for perfect mixing to 10 for poor mixing) is applied as a multiplier to determine the actual required ACH. The mixing factor is determined quantitatively by CFD analysis or experimentally testing space configuration (5,7). Also, an experienced HVAC engineer who releases smoke at a number of locations in the enclosure and observes the smoke movement can find it qualitatively (5).

- **Pressurization:** Air pressurization or directional airflow in an animal facility is used to contain contaminated air in localized areas and prevent its spread to clean areas. The room and cage ventilation systems should be designed and balanced so that air flows from less contaminated (clean) to more contaminated (less clean) areas (5).

Positive pressure is traditionally used in barrier and procedural rooms, as well as individually ventilated caging (IVC) systems. This process relies on air leakage from the enclosure to exclude airborne contaminants from the space; i.e. bioexclusion. Bioexclusion is expensive to acquire, maintain, and operate since it necessitates a pressurized system with blowers that generate noise, vibration, heat gain, and high turnover of dry air. Forced air tends to migrate in corners and to recirculate behind air obstructions. Air migration and recirculation create turbulences, eddies, and dead-air spaces, thus requiring higher ventilation rates due to poor air mixing factor. Under these conditions, it is impossible to control, optimize, and maintain IAQ standards. However, positive pressure protects the animals from airborne contamination.

In rooms and cages, negative pressure is attained by balancing exhaust air at a higher rate than pressurized air is being supplied (i.e., air balancing) or by exhaust ventilation.

Negative pressure is used in isolation and containment rooms, as well as in IVC and exhaust ventilated caging (EVC) systems with closed-system cages. Negative pressure prevents contaminated air from escaping from a room and/or a cage to another area of the facility (5); i.e., biocontainment. In rooms and cages, negative pressure is attained by balancing exhaust air at a higher rate than pressurized air is being supplied (i.e., air balancing) or by exhaust ventilation. Either the building's HVAC system or a portable exhaust fan assists exhaust ventilation. Dampers and valves or a variable speed fan can respectively control it. In cages, exhaust ventilation requires a low differential static pressure (EVC = 37.5 Pascals) when compared to air balancing (IVC = 125 Pascals). Exhaust ventilation under low pressure can create a single-pass directional airflow with perfect air mixing factor, thus effectively eliminating heat loads and odors. Single-pass exhaust ventilation is cheaper to operate than pressurized air balancing because of a reduced average total heat gain formula. This means that a minimal recommended ACH can be used instead of a higher required ACH._Unlike air balancing, exhaust ventilation effectively controls the direction of airflow between two adjacent areas. Negative pressure can easily control, optimize, and maintain IAQ standards. Thus, it can provide environmental stability at room and cage levels, while protecting the animals and workers from airborne contamination (10,11).

Source Control with LED (Local Exhaust Devices)

LEDs are used to control airborne contaminants at the source. LEDs include biosafety cabinets (BSC), capture exhaust units, and exhaust ventilated cage rack systems (EVC) that exhaust directly to outside. Direct exhaust ventilation is a preferred source control technique, and it is often the most efficient and economical way to contain animal-related airborne contaminants because it captures these contaminants near their source, before they can disperse in the environment (5). All LED have air cleaning units, a leak-free enclosure, and a unique single-pass ventilation design to ensure a perfect mixing of filtered air inside the enclosure. This type of equipment protects animals, personnel, and the environment from airborne contamination.

BSC/Hood/ATS (Animal Transfer Station): The BSC Class II, Type B2 with total direct exhaust and the BSC Class III, Negative Pressure Glovebox prevent infectious droplet nuclei and other contaminants in the cabinet from escaping into the room. Hoods such as fume hoods, range hoods, and down-draft tables are used to contain and eliminate noxious chemical fumes, odors, and other airborne contaminants. Both BSC and hoods exhaust directly to the outside, protecting animals, personnel, and the environment. If the air is discharged into the room instead of directly outside, a HEPA (high efficiency particulate air) filter is incorporated at the discharge duct or vent of the device. For instance, the HEPA filtered BSC Class II, Type A2, laminar flow unit provides 70% recirculated and 30% exhaust to room. Conversely, an ATS, Class 100 vertical flow recirculating clean bench exhausts into the room. The operational differences between BSC (Class II, A) and ATS are 99.9%/99% personnel and 99.8%/98% environmental reduction of airborne contaminants, respectively. Both of these types of cabinets protect animals and personnel.

Capture Exhaust Units (CEU): The most effective way to control emissions of airborne contaminants is to “capture” them at the point of release and remove them by exhaust ventilation before they are dispersed into the enclosure air. This capture technique is called local exhaust ventilation (LEV). The reasons why LEV is so effective are only a relatively small volume of air is required to capture and remove airborne contaminants released at a point source compared to the very large volumes required to try to change the air in an entire area of an enclosure or a building; and capture of contaminants at the source point can virtually eliminate any exposure of animals and workers to the contaminants (12). CEUs are used directly above contaminant-generating surface areas such as necropsy tables, cabinets, isolators, or IVCs that exhaust to the outside. IVC manufacturers offer two types of exhaust capture systems in their racks. One system allows capture of the air exiting the exhaust blower indirectly through the facility's exhaust HVAC system. The other requires racks, from which the exhaust blowers have been removed, to be connected directly to the facility's HVAC system. The racks, thus, provide an exhaust draw with direct connection to outside (13). CEUs remove and avoid buildup of animals' heat load, odor, and airborne contaminants in the secondary enclosure, supporting IAQ standards at the room level. Thus, CEU protects animals, personnel, and the environment.

Exhaust Ventilated Caging System (EVC): EVC with closed-system design, single-pass ventilation, and direct exhaust ventilation are used as LED. EVC can be designed to avoid the use of dedicated supply and exhaust blowers (14). Instead, EVC rely upon the facility's HVAC system to provide a low-velocity exhaust draw with a direct connection to outside. The cage rack single-pass ventilation rate can be adjusted and controlled at the exhaust point with dampers and/or constant volume valves. Using low-velocity, filtered room-air supply to purge each cage in single-pass ventilation takes advantage of the animal room as a mixing chamber to supply adequate oxygen, T, and RH and to provide comfortable, optimal, and stable environmental conditions. Also, exhaust ventilation at both cage and rack level removes airborne contaminants and avoids accumulations of heat and moisture (14). EVC provides IAQ standards with optimal environmental conditions at room and cage levels, thus protecting animals, personnel, and the environment.

> *There is a direct correlation between time of exposure and risk of environmental contamination and variation—the longer the exposure, the higher the risk.*

Air Cleaning

Air cleaning devices reduce and remove air particulates from recirculated, non-discharged, and contaminated air. Filtration and impaction can be used as methods of air cleaning to supplement other engineering controls.

Filtration: Retention of particles on filter media is by direct interception; i.e. mechanical capture of a particle by the filter. Filter retention efficiencies are rated according to their nominal or absolute pore size. Nominal pore size rating describes the ability of the filter media to retain particles at the rated pore size and larger. Processing conditions, such as operating velocity, pressure, and concentration of contaminants have a significant effect on the retention efficiency of the media.

HEPA filters: Defined as air-cleaning devices that have a removal efficiency of 99.97% of particles 0.3 micron in diameter. Due to its resistance to air, HEPAs are pleated and air is forced through it so that HEPA-filtered units are validated at a velocity of 0.5 meters per second (m/s; 100 feet per minute [fpm]. If HEPA filters are used beyond their design face velocity, such as with IVC blowers, they loose their removal efficiency. Doubling the air velocity through a HEPA filter can cause a 10-fold increase in particle penetration (6). HEPA filters can be used to clean air before it is recirculated within a room or a cage (5).

Spunbonded Polyester Media: Spunbonded polyester media are used on filter-top cages and vent ports of closed-system cages and have 100% retention efficiency of particles 22 microns and bigger. This material is validated at a low-velocity of 0.025 m/s (5 fpm). However, its efficiency can increase by adding other means of filtration, such as inertial impaction, gravitational settling, electrostatic attraction, and Brownian motion. For instance, closed-system cages with vent port filter units have 100% collection efficiency at 1 micron and bigger when sandwiched by stainless steel screens (14,15). Absolute pore size rating specifies the pore size at which a challenge organism of a particular size will be retained with 100% collection efficiency under strictly defined test conditions. Among the conditions that must be specified are test organism (or particle size), velocity, pressure, concentration, and the detection method used to identify the contaminant. For example, HEPA filters have an absolute 0.3 micron particle pore size rating at a design face velocity of 0.5 m/s (100 fpm). Filter media on static filter-top and closed-system cages also have an absolute 0.3 micron pore size rating at design face velocity of 0.025 m/s (5 fpm) (15).

Impaction: Capture of particles on surfaces occurs in a network of overlapping surfaces or a tortuous path because a particle's inertia carries it in a straight line even when the air stream bends. Inertial impaction prevents the migration of contaminants inside an area or enclosure protected by a tortuous path or a labyrinth seal, respectively. Tortuosity, as its name implies, is the removal of airborne contaminants by creating a path so tortuous that it becomes trapped. Tortuous paths such as corridor systems, double-door airlocks, anterooms, and procedural areas are used in barrier and biocontainment facilities to preventing dispersion of particles. A labyrinth seal between a container and a lid utilizes a tortured path so air contaminants become trapped by impaction on surfaces. The use of a labyrinth seal with at least four contact surface areas is a preferred method over gasket or rubber seal for caging (16).

In addition to the three engineering controls we have discussed (ventilation, LED, and air cleaning systems) it is important that IAQ engineering controls minimize exposure of experimental animals and staff to airborne contaminants. There is a direct correlation between time of exposure and risk of environmental contamination and variation—the longer the exposure, the higher the risk. As per table S3-1 provided in the *Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities*, the time required for required ACH to achieve a removal efficiency of 99% of airborne contaminants is expressed in number of minutes (5). The efficiency depends on the choice of IAQ engineering controls.

For example, a room set at 15 ACH of single-pass ventilation with a mixing factor of two that is equipped with a recirculation IVC system, ATS, and other equipment that exhaust to room would require 36 minutes. The same room equipped with single-pass EVC system, BSC, and other LED that exhaust to outside would require two minutes. On the other hand, a room set at 15 ACH of recirculation ventilation with a mixing factor of eight that is equipped with a recirculating IVC system, ATS, and other equipment that exhaust to room would require 144 minutes. The same room equipped with single-pass EVC system, BSC, and other LED that exhaust to outside would require seven minutes.

Caging systems' ventilation efficiencies can be evaluated by smoke tests. Cage engineering control efficiencies are expressed in number of minutes required for a removal efficiency of 99% smoke (12). EVC caging, such as the M.I.C.E.® system (Animal Care Systems, Littleton, CO; www.AnimalCareSystems.com), set at 0.02 m/s for 20 ACH of single-pass ventilation with a perfect mixing factor of one, would require four minutes. IVC caging such as SealSafe® (Techniplast, Varese, Italy; www.tecniplast.it) set at 0.15 m/s for 60

ACH of recirculation ventilation with a mixing factor of eight would require 20 minutes.

Discussion

Cost-effective IAQ engineering controls for the animal facility should include the use of single-pass ventilation at minimal ACH under negative pressure combined with LED and low-velocity absolute filters. Such control would efficiently eliminate airborne contaminants at their source of generation before dispersion and prevent recirculation of contaminated air. This combination of controls may be the best solution to provide high IAQ standards at room and cage levels, minimize experimental variables, and contain costs. Also, using an EVC system with direct exhaust connection to the outside would further reduce the ACH required. EVC will eliminate airborne contaminants and most of the heat loads before transfer through cage surfaces to the room. In fact, using a closed-system caging on an exhaust ventilated rack, such as the M.I.C.E.* system, eliminates 95% of the heat load expected to be generated by the largest number of animals. For this example, the average-total-heat-gain formula would have a multiplier of 5%. Moreover, such EVC driven by the building's exhaust HVAC system instead of electric blowers would lower the total cooling load expected to be produced by both animals and non-animal sources. A low ventilation rate might save on HVAC installation, operation, and life cycle costs; on building commissioning, room balancing, and energy requirements; and on maintenance, service, calibration, and validation of fans and filters.

Conclusions

It is important to integrate the choice of IAQ engineering controls in the early development of an animal facility design. Animal facility designers need to balance the cost of engineering controls against the needs of the biomedical research institutions and breeding facilities. Fundamental needs are to provide optimal and stable environmental conditions at both room and cage levels for the production of valid data, as well as the health and well-being of laboratory animals and workers. A good recommendation is to use the services of HVAC engineers and CFD professionals that are familiar with animal facility operations. For instance, single-pass ventilation at low required ACH with adequate air cleaning seems to be the engineering control method of choice to ventilate animal rooms and LED, including BSC and EVC. On the other hand, choosing to ventilate a room or a cage by recirculation ventilation with poor air mixing might seem cheaper up front, but its cost of ownership and life cycle are, in the long run, going to be more expensive than single-pass ventilation. Also, it might exacerbate physiological, experimental, and environmental stressors on caged animals as well as jeopardize the production of valid data.

The choice of engineering controls can have an effect on species-specific IAQ standards, as engineering controls will affect the health and well-being of the animals including reproductive performance; animal care and research staff; experimental variability; flexibility of facility; safety; and cost-effective management of high animal population densities. Also, the selection of the engineering controls will affect the cost of building, renovating, expanding, maintaining, and operating conventional, barrier, and/or biosafety facilities significantly. Selection of effective controls leads to significant savings on construction, retrofitting, and operation costs, resulting in a cost payback period of less than a year (12). Institutions that have made an appropriate choice of engineering control methods early on during the design and planning process will reap the benefits for the life of the facility.

References

1. **Ruys, T.** (ed.). 1991. Handbook of facilities planning, vol. 2. Laboratory animal facilities. AIA, NY.
2. **National Research Council.** 1996. Guide for the care and use of laboratory animals. National Academy Press, Washington, D.C.
3. **National Research Council. 1997**. Occupational health and safety in the care and use of research animals. National Academy Press, Washington, D.C.
4. **National Institutes of Health.** 2003. NIH design policies and guidelines. [Online] Available at http://des.od.nih.gov/eWeb/policy/html/index.html. Accessed 07/24/04.
5. **Centers for Disease Control.** 1994. Guidelines for preventing the transmission of mycobacterium tuberculosis in health-care facilities, supplement 3: Engineering controls. [Online] Morbidity and Mortality Weekly Report, vol. 43. Available at www.phppo.cdc.gov/mpep/pdf/tli/rr4313.pdf. Accessed 07/24/04.
6. **Kowalski, W. J., P. E. Bahnfleth, and D. D. Carey.** 2002. Engineering control of airborne disease transmission in animal laboratories. Contemp. Top. Lab. Anim. Sci. **41** (**3**): 9-17.
7. **Morse, B. C., S. D. Reynolds, D. G. Martin, A. J. Salvado, and J. A. Davis.** 1995. Use of computational fluid dynamics to assess air distribution pattern in animal rooms. Contemp. Top. Lab. Anim. Sci. **34** (**5**):65-69.
8. **Rivard, G. F., D. E. Neff, J. F. Cullen, and S. J. Welch.** 2000. A novel microisolation container for caging animals: Microenvironmental comfort in a closed-system filter cage. Contemp. Top. Lab. Anim. Sci. **39** (**1**):22-27.
9. **American Society of Heating, Refrigeration, and Air-Conditioning Engineers.** 1993. ASHRAE Handbook: Fundamentals, I-P Edition. Atlanta.
10. **Myers, D. D., E. Smith, I. Schweitzer, J. D. Stockwell, B. J. Paigen, R. Bates, J. Palmer, and A.L. Smith.** 2003. Assessing the risk of transmission of three infectious agents among mice housed in a negatively pressurized caging system. Contemp. Top. Lab. Anim. Sci. **42** (**6**):16-21.
11. **Schweitzer, I.B., E. Smith, D.J. Harrison, D.D. Myers, P.A. Eggleston, J.D. Stockwell, B. Paigen, and A.L. Smith**. Reducing exposure to laboratory animal allergens. Comp. Med. **53**: 487-492.
12. **Rivard, G.F.** 2004. Personal communication.
13. **Bilecki, B.** 2002. HVAC: Making the connection. Animal Lab News **1** (**1**): 5-8.
14. **Rivard, G.** 2001. Exhaust ventilated caging. [Online] Available at www.animalcaresystems.com/pdf 4microenviron mentalcomfort1.pdf. Accessed 07/24/04
15. **Canard, G., P. Hardy, and F. Veillet.** 2001. Microbiological validation of the M.I.C.E.* caging system. [Online] Available at www.animalcaresystems.com/pdf/manualappendixd.pdf. Accessed 07/24/04.
16. **Orcutt, R.P., R.S. Phelan, and J.G. Geistfeld.** 2001. Exclusion of mouse hepatitis virus from a filtered, plastic rodent shipping container during an in transit field challenge. Contemp. Top. Lab. Anim. Sci. **40** (**4**):32-5.

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