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ANIMAL FACILITY VENTILATION AIR QUALITY AND QUANTITY

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ABSTRACT

Ventilation influences an animal's physical environment by removing thermal loads, diluting gaseous and particulate contaminants, and controlling heat loss and gain to the animal rooms. Early studies recognized the importance of controlling air quality and providing odor-free environments through frequent changes of room air. However, the concept of volumetric exchange rate is preferable to room air changes per hour because the latter does not account for the spatial dimensions of the room. Further, expressing ventilation rates as volumetric changes per occupant allows for the calculation of cage air exchange rates, which should more effectively ventilate the primary enclosure and allow for differences in room size and cage fractional loads. Because gaseous contamination is a function of generation rate and mass airflow rate of odor-free air, the effectiveness of air changes per hour in controlling odors or gaseous contaminants is limited. In an animal facility, the principal uses of energy are heating, ventilating, and air-conditioning (HVAC) systems; fans; energy pumps; and miscellaneous equipment. Of these, about 61% of the energy use may result from service water and HVAC systems. For all of these reasons, additional research is needed to determine the optimum ventilation air quality and quantity for animal facilities.

INTRODUCTION

Concern for the health and well-being of laboratory and other animals has resulted in both federal legislation (U.S. Congress 1966-1985) and regulation (*CFR* 1991). The Animal and Plant Health Inspection Service (APHIS) of the U.S. Department of Agriculture (USDA) is the agency responsible for administering the Animal Welfare Acts (U.S. Congress 1966-1985). All facilities that house animals for research, education, experimentation, exhibition, or testing are subject to unannounced inspections by personnel of the Regulatory Enforcement and Animal Care (REAC) unit of APHIS. In addition to USDA federal regulations (*CFR* 1991), the primary guideline providing recommendations for the care and housing of laboratory animals used in research, education, or testing is the *Guide for the Care and Use of Laboratory Animals* (CGCULA 1985), which is hereinafter referred to as the Guide. Information on the most common agricultural animals used in teaching and research, including animal production systems, is contained in the *Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching* (CDAACG 1988).

Although the contents of the *Guide* are directly applicable only to institutions receiving Public Health Service funding, *Guide* contents should be followed in the operation of all institutional animal facilities and programs receiving funds from any public or voluntary health care agency. The American Association for the Accreditation of Laboratory Animal Care (AAALAC), a nonprofit corporation that accredits laboratory animal care and use programs, uses the *Guide* as its primary reference document. The National Institutes of Health accept full accreditation by AAALAC as assurance that the animal facilities are in full compliance with Public Health Service policy (PHS 1986).

A key issue in all the above documents is the maintenance of environmental quality in an animal facility. Regardless of the species of housed animals, their behavior, physiology, and affectivity can be influenced by physical (e.g., heat, water vapor), organismic (e.g., sex, age), and adaptive (e.g., activity, body covering) factors (Rohles 1971). In this paper the emphasis is on physical factors (Figure 1) (Besch 1980, 1985); the role of organismic and adaptive factors is discussed in detail elsewhere (Lindsey et al. 1978; Moreland 1975; Newberne and Fox 1978; Rohles 1971).

Maintenance of the microenvironment at desired levels of temperature, humidity, and contamination (gaseous and particulate) contributes to the physiological well-being of the animal during routine housing or animal transport. When the physical factors are not properly controlled, physiological and psychological responses may occur and the behavior and metabolism of the animal may be affected (Baetjer 1968; Bellhorn 1980; Besch and Brigmon 1991; Peterson 1980; Rohles 1971).

Nonetheless, much of what is known about the design of heating, ventilating, and air-conditioning (HVAC) systems in animal facilities is based on experience, as few systematic studies have been completed on this subject (Besch 1985). Further, construction guidelines are somewhat broad and allow for professional judgment (CGCULA 1985). The purpose of this paper is to review the current knowledge and demonstrate that additional research is needed to determine the optimum ventilation air quality and quantity for animal facilities.

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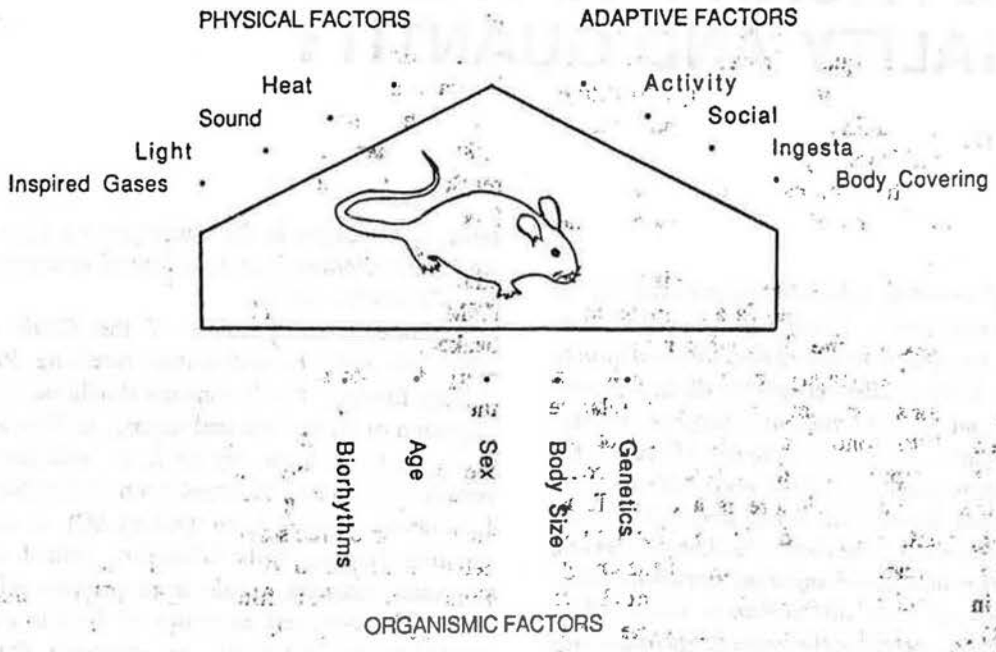

Figure 1 *Interactive characteristics of an animal's bioenvironment (adapted from Rohles [1971]).*

VENTILATION

The importance of ventilation air quality and quantity has been known for many years (Yaglou et al. 1936) and early studies were concerned with providing "odor-free" environments (Munkelt 1938). The notion that controlling gaseous contamination would keep odors below "objectionable levels" led to the recommendation that 20% outside air (i.e., 2.5 air changes per hour) should be used during recirculation of animal room air (Munkelt 1938). Activated carbon filters (Munkelt 1948) and recommended further increases in room air changes per hour (Runkle 1964) were utilized to keep odors below objectionable levels for humans. This led to the concept of room air changes per hour as the primary means of controlling odors in animal facilities (Munkelt 1948; Runkle 1964), but the effectiveness of ventilation apparently was not a serious consideration.

Effective ventilation of animal facilities is required to supply adequate oxygen, dilute gaseous and particulate contaminants, control room temperature and humidity (Besch 1991), and control effects of infiltration and exfiltration (Clough and Gamble 1976; CGCULA 1985; Edwards et al 1983). To be effective, ventilation air must be coupled with the animal's microenvironment to maintain acceptable thermal, gaseous, and particulate conditions. This coupling can be passive or supply-coupled (Woods et al. 1975a). Most animal caging systems are passively ventilated; the exceptions are those using laminar airflow principles (Beall et al. 1971; McGarrity and Coriell 1976). As a consequence, the cage air exchange rate not only depends on the room air distribution pattern and air exchange rate but also on the mass (i.e., water vapor, gaseous contaminants) and energy (i.e., animal heat) loads of the cage. If cage air exchange results mainly from natural convection, cage ventilation will be diminished (Besch 1975).

Thus, effective ventilation is not attained by room air changes per hour but by volumetric exchange rate per animal (Besch 1980; Woods 1978), which ensures that ventilation air actually reaches the animal's habitat or microenvironment. This is accomplished by controlling room air distribution, air diffusion, and the effects of trans-cage coupling. Control of the animal's cage microenvironment requires knowledge of the relationships between the cage and surrounding macroenvironments (Woods 1975).

It is generally accepted that dissipation of sensible (nonevaporative) and latent (evaporative) heat loads is accomplished using outdoor or recirculated air. Dilution of gaseous or particulate contaminants usually involves outside air; particulates also may be filtered. Hence, it is customary to use the term *room air exchange rate* when referring to thermal exchange and *ventilation rate* when referring to mass dilution (Besch 1980; Woods et al. 1975b). Ventilation rates of 10 to 15 outside air changes per hour have been specified for laboratory animal rooms, but other methods of providing equal or more effective ventilation are acceptable (CGCULA 1985).

ANIMAL MICROENVIRONMENTS AND MACROENVIRONMENTS

Differences between microenvironments and macroenvironments have been recognized for about 100 years (Henriques and Hansen 1904), but their importance relative to animal facilities was not clearly demonstrated until the early 1940s (Reyniers 1942). Even at that time, proper ventilation was defined as adequate air exchange without drafts; adequate air meant sufficient air change to dilute gaseous and particulate contaminants. But the ventilation of cages was to be accomplished by ventilating the room ". . . in such a manner that the cages are bathed in a shower of air, which is drained off near the floor of the room" (Reyniers 1942).

According to the *Guide*, primary enclosure is the same as the microenvironment, which often is an animal cage. When animals are housed on the floor of a room or in runs, the room or run is the primary enclosure. However, because recommendations for temperature and relative humidity are intended to control the conditions of the room, they are not appropriate for the animal's microenvironment when the primary enclosure is a cage. Thus, control of heating, ventilating, and air conditioning of animal facilities requires not only knowledge of the energy and mass factors in an animal's microenvironment (Besch 1980; Serrano 1971) but also cage design characteristics. Regarding the latter, it has been reported (Woods et al. 1975b) that expanded metal flooring in cages tends to minimize differences between cage and room when the cages are passively ventilated by room air.

Significant dry-bulb (Δt_{db}) and dew-point (Δt_{dp}) temperature gradients have been reported (Besch 1975; Murakami 1971) between the animal cage and room; this gradient is increased in cages containing filter bonnets (Besch 1980; Serrano 1971). Although cage filters appear to provide some control of mass contaminants, such as water vapor and viable particulates (Besch 1980; Schneider and Collins 1966), they also cause reduction in air exchange (Besch 1980). It has been reported (Besch 1980) that gases such as ammonia (molecular weight = 17) respond much like water vapor (molecular weight = 18) in animal cages. Reported dew-point temperature gradients between cage and room suggest that the moisture content inside filtered cages could be 47% to 75% higher than in the room (Besch 1980). Thus, if cage filters can prevent the release of water vapor, intracage ammonia concentrations also could rise and, in those cases, the increase in NH_3 would be approximately the same as the increase in water vapor. Ammonia concentrations regularly found in rat cages have been shown to cause lesions in the nasal passages of rats (Broderson et al. 1976).

On the other hand, the concentration (C) of gaseous contaminants (e.g., ammonia) depends on the generation rate (G) of the substance and the mass flow rate (M) of odor-free air (Figure 2) as described by the equation

$$C = G/M. \tag{1}$$

That is, when the mass airflow rate is held constant, the concentration of a substance is directly related to its generation rate. When the generation rate is constant, the concentration is inversely related to the mass airflow rate. Because of the relationship between generation rate and air changes per hour (Figure 2) and assuming a steady-state generation rate of ammonia and no recirculation of air, the increase in room air changes per hour does not greatly reduce the concentration of ammonia at equilibrium (Besch 1985). It has been reported that volumetric air changes reach diminishing returns at about 15 air changes per hour (Moreland 1975).

The Δt_{db} and Δt_{dp} are influenced by both design characteristics and animal loads. In studies using simulated (SIMOC) rats, animal loads were determined using 250-mL beakers filled with 200 mL of water and completely submerged resistors providing a 2.9-watt load. By controlling the electric current to a submerged resistor, the calculated sensible and latent heat loads from one resistor simulate the thermal load of five rats. The total simulated heat load of the animal shipping containers (ASC) results from varying the number of resistors (i.e., SIMOCs). The relationship between Δt_{db} and Δt_{dp} and simulated animal load was obtained using both filtered and unfiltered animal shipping containers (Table 1). For unfiltered ASC, there is a direct relationship between Δt_{db} and Δt_{dp} as a function of animal load. However, both the Δt_{db} and Δt_{dp} are greatly elevated in the filtered compared to the unfiltered ASC; the Δt_{dp} is higher in the filtered compared to the unfiltered ASC at any given animal load. The rate of increase in Δt_{dp} is about the same for filtered (i.e., slope = 0.76) compared to unfiltered (i.e., slope = 0.75) ASC. Although a similar effect was observed during Δt_{db} measurements, the difference in Δt_{db} between filtered and unfiltered ASC is less than for Δt_{dp}.

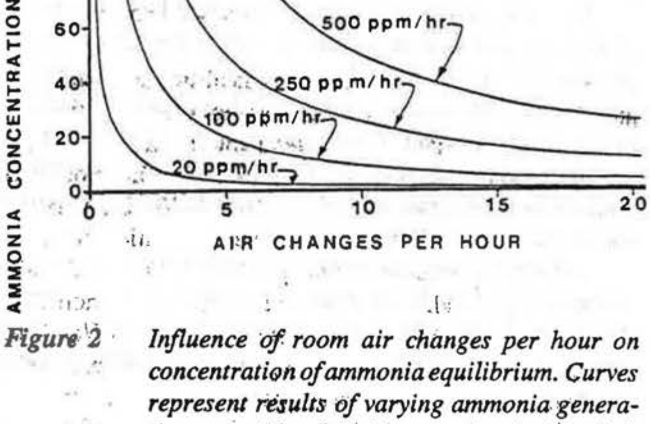

Figure 2 *Influence of room air changes per hour on concentration of ammonia equilibrium. Curves represent results of varying ammonia generation rates (ppm/h) with no recirculation of air through the animal room (from Besch [1985]; reprinted with permission of the American Physiological Society).*

TABLE 1
Summary of Dry-Bulb (DBT) and Dew-Point (DPT) Temperature Gradients (mean ± SE) for All Single-Compartment Animal Shipping Containers

Container Type	n[1]	Simulated Load	Temperature Gradient (°C)	
			DPT	DBT
Unfiltered	5	10 rats	5.41 ± 0.36	4.28 ± 0.09
Unfiltered	5	20 rats	6.27 ± 0.22	5.50 ± 0.19
Unfiltered	5	30 rats	8.56 ± 0.28	9.06 ± 0.25
Filtered	4	10 rats	8.56 ± 0.26	5.17 ± 0.37
Filtered	4	20 rats	15.13 ± 0.23	11.78 ± 0.20
Filtered	4	30 rats	23.02 ± 0.31	14.77 ± 0.26

[1]n = number of shipping containers.

ROOM AIR DISTRIBUTION AND DIFFUSION

Air is typically supplied to any conditioned space or room via ductwork that opens into the animal room through diffusers, registers, or grilles. In order to maintain the environmental quality of the primary enclosure, the ventilation air must sustain acceptable thermal conditions and control contaminants of the animal's microenvironment. Typically, room air is not recirculated because of the possibility of cross-contamination of primary enclosures. Also, it is recommended that multiple species not be housed in the same room (CGCULA 1985; FDA 1988).

Animal facilities generally employ three different types of ventilation systems: open, closed, and barrier (Shaw 1976). The open system allows free access of personnel, animals, and materiel. The closed system contains hermetically sealed rooms or spaces that are entered through air locks, dunk tanks, autoclave locks, or gastight shower locks; all material is sterilized prior to entry (Reyniers 1964). In both open and closed systems, animals may come into contact with investigators or caretakers. The third, or barrier, system isolates animals from humans because these systems are designed to contain and prevent the release of microbiological, radiological, or chemical contaminants (Henke 1978).

To mitigate the problem of providing large quantities of conditioned ventilation air to empty rooms or rooms partially filled with occupied animal cages, the concept of animal cubicles was developed (Dolowy 1961). Cubicles result from dividing a large room into smaller animal housing units. Cubicles are used to quarantine or isolate animals or to separate animals by species, microbiological status, and project (Hessler 1991).

However, cubicles possess special HVAC requirements because high heat loads often are contained in a comparatively small area. Two basic ventilation options have been reported (Ruys 1988) but the choice is a matter of judgment:

- Supply air from the ceiling of the aisle is directed under the door of the cubicle and exhausted at the ceiling of the cubicle.
- Each cubicle is provided with individual supply and exhaust using either positive or negative pressure in the cubicle.

Because one of the disadvantages of these options is a short-circuiting of air from supply to exhaust (Hessler and Roberts 1989; White et al. 1983), it may be difficult to calculate the effective ventilation rates required to maintain microenvironmental temperatures based on the calculated heat loads.

ROOM-COUPLED AND SUPPLY-COUPLED CAGE VENTILATION

An air exchange rate that depends on cage heat load, room air distribution, cage location in the room, and natural convection currents has been referred to as a room-coupled system (RCS) (Woods 1975). These systems are passively coupled to room ventilation rate, $\dot{V}$ ($L \cdot s^{-1}$), via an experimentally derived room-coupling coefficient, α, which represents that portion of the room air exchange rate that occurs in the cage (Woods et al. 1975a). The numerical values for α depend on the volume of the room (Woods et al. 1975a). Further, the relationship between cage ventilation rate, $\alpha\dot{V}$ ($L \cdot s^{-1}$), and room ventilation rate per unit floor area can be used to determine the required room ventilation to achieve the desired cage environment. Calculations of volumetric changes per occupant using the terms α and $\dot{V}$ in the microenvironmental model (Woods et al. 1975a) allow for differences in room size as well as corresponding cage fractional loads.

For example, assuming that a cage air exchange rate of 14 $L \cdot s^{-1}$ (30 cfm) was necessary to maintain the thermal neutrality of a dog, the necessary room air exchange rate for an RCS would be 0.38 $L \cdot s^{-1} \cdot 0.0929\ m^{2-1}$ (0.8 $cfm \cdot ft^{2-1}$). Therefore, 1,322 $L \cdot s^{-1}$ (2,800 cfm) would be required for a 325-m^2 (3,500-ft^2) laboratory. Because the required air changes per hour depend on ceiling height, if the described laboratory's ceiling height was 2,438 mm (8 ft), then 8 air changes would be required; for a ceiling height of 3,048 mm (10 ft), 12.5 room air changes per hour would be required (Woods et al. 1975a).

On the other hand, when conditioned air is provided directly to the cage environment, cage air exchange is referred to as a supply-coupled system (SCS). In the latter, the cage air exchange rate can be determined precisely. Using the RCS and SCS models, a cage performance characteristic (T) can be calculated (Woods et al. 1975b):

$$T = t_c - t_i / t_r - t_i \qquad (2)$$

where

T = cage performance characteristic,
t_c = cage dry-bulb temperature (°C),
t_r = room air dry-bulb temperature sampled at exhaust (°C),

t_i = room air dry-bulb temperature sampled at supply (°C).

The T allows for accurate prediction of the room air exchange rates that are needed to obtain the desired cage microenvironmental condition (Woods et al. 1975b). For example, if a supply air temperature (t_i) of 14.5°C is required to maintain the room at 24.5°C (t_r) at 7.5 air changes per hour and the desired cage temperature should not exceed 28°C (t_c), a T value of 1.34 is obtained using Equation 2. In other words, cages with a T value of 1.34 or less at 7.5 room air changes per hour would provide an acceptable cage microenvironment. The benefit of using these models is that there would no longer be a need for specifying room ventilation rate as an arbitrary number of air changes per hour (Woods et al. 1975b).

ENERGY COSTS OF ANIMAL FACILITY VENTILATION

The requirement that animal facilities be operated on a 24-hour-a-day, seven-day-a-week basis and ventilated with 100% outside air results in a large ventilation load. This, in turn, results in large energy requirements because outside air must be conditioned before entering the animal rooms or cages (Gorton 1975). Compared to office buildings, laboratory facilities are energy intensive and use 10 to 30 times as much energy per square meter (Spielvogel 1978).

The key elements requiring energy include the heating, ventilating, and air-conditioning (HVAC) and service water systems (Gorton 1978). These account for about 61% of the energy used in a research laboratory building (Spielvogel 1978). The thermal loads result from internal occupants, lights, motors, and cage working equipment. It has been suggested that thoughtful design can result in cost-effective systems that will significantly reduce energy costs (Gorton 1978).

One obvious way to reduce energy use is to decrease the amount of air used by the HVAC system. This could be accomplished without a loss in air quality by utilizing the cage performance characteristics to maintain the specific microenvironmental conditions (Woods et al. 1975b). Another suggested strategy would involve improved energy management through the use of energy recovery devices. Examples of such devices and their appropriateness for use in animal facilities have been described elsewhere (Gorton 1978). The common denominator of all heat recovery systems is that energy recovered from exhaust air would be used to heat intake air. A detailed cost analysis must be completed prior to selecting a system.

It has been estimated that HVAC systems using 100% outside air constitute about 35% of the construction costs of an animal facility. The use of recirculated air may save 20% of this cost. On the other hand, a 50% reduction in the capability of providing 15 outside air changes per hour (i.e., using only 7 to 8) could save an estimated 40% of the start-up costs (Alschuler 1963) in addition to the savings accrued from reduced operating costs associated with the reduction of outside air changes per hour.

ALTERNATIVES TO ONE-PASS AIR

Because ventilation plays a role in the elimination of gaseous and particulate contaminants from the air in an animal facility, it helps to prevent the airborne infection of research animals. This has led to the perception that outside air changes to animal rooms cannot be reduced or animal room air recirculated; thus, the animal facility is ventilated with "one-pass" outside air. Nonetheless, guidelines (CGCULA 1985) for ventilating animal facilities include provisions for the use of alternative methods of providing equal or more effective ventilation.

Gaseous contaminants usually are controlled by dilution, while particulates are removed by air filtration or electrostatic precipitators. Other odor control methods include washing, scrubbing, condensation adsorption, chemical absorption, and deodorants. While the use of these methods could allow the use of recirculated air and potentially result in a reduction of required outside air changes per hour, the start-up and maintenance costs of such systems must be evaluated to determine if they are cost-effective.

In addition to one-pass air, laminar airflow (LAF) techniques have been successfully employed to maintain "clean" areas in medical and biological investigations and to keep small animals free from exposure to normal environmental bacteria. An LAF system (Beall et al. 1971) has been successfully used to prevent cross-contamination of rats housed in conventional open cages and to prevent rats with respiratory infections from contaminating healthy rats. The efficacy of laminar flow cabinets in protecting germfree mice from infection also has been demonstrated (van der Waaij and Andreas 1971). But LAF systems are expensive to purchase and maintain, and their use in animal facilities has had only limited appeal.

Mass airflow (MAF) is a modification of LAF and utilizes high-efficiency particulate air (HEPA) filtration. When applied to animal rooms, HEPA-filtered air is directed to a plenum chamber above the room ceiling and enters the room through openings in the ceiling. Air moves vertically through the room at velocities lower than LAF. Because the lower velocity requires a smaller HEPA filter surface, the purchase and operating costs of an MAF system should be lower than for an LAF system. It has been reported that use of the MAF results in a 40% reduction in energy (McGarrity and Coriell 1976), but MAF has not been used extensively in animal facilities.

Activated carbon also has been used to remove some gaseous contaminants (Munkelt 1948) but has been shown to be less effective in removal of substances such as ammonia. Because ammonia has a high water solubility, chemical scrubbers are effective in removing this contaminant (Jeszenka et al. 1981a). HEPA filters and chemical scrubbers are equally effective in removing bacteria from recycled air (Jeszenka et al. 1981b). Cubicles have been reported to be cost-effective in housing animals under some circumstances (Hessler 1991) and in achieving limited biohazard containment (White et al. 1983).

CONCLUSIONS

1. Interest in and concern for environmental quality within animal facilities can be traced to the first publication of the *Guide for the Care and Use of Laboratory Animals* in 1963 and its subsequent revisions (CGCULA 1985). Since that time, much progress has been made in defining environmental requirements to reduce physiological and psychological stressors and ensure the health and well-being of the animals.
2. Although communications between designers and users of animal facilities have improved recently, there are still opportunities for meaningful dialogue in establishing priorities. For example, options for energy conservation should be developed as cost-effective alternatives to one-pass air. These should include comparisons of initial costs, projected energy savings, anticipated changes in gaseous and particulate contaminants, operational costs, reliable preventive maintenance systems, and emergency operation.
3. Alternatives to ventilating animal facilities with 100% outside air should be studied. If recirculation of air is considered an option, care must be exercised to ensure that all particulate and toxic gaseous contaminants have been removed. Special attention also must be given to systems maintenance because in the past this often has rendered air treatment ineffective. In particular, consideration should be given to maintaining the animal's microenvironment at the optimal temperature and humidity conditions without diminishing air quality.
4. Anticipating needs that require further investigation and pursuing research initiatives are obvious ways for the biomedical community to deal with these issues. Use of analytic and scientific methods will generate new information that will allow elaboration of consensus standards. Ultimately this enlightened approach will best serve the researcher/teacher as well as the animal. Unless progress is made in the needed areas, heightened societal interest in animal welfare may result in legislatively mandated solutions.

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