CHAPTER 22

ENVIRONMENTAL CONTROL FOR ANIMALS AND PLANTS

THE design of plant and animal housing is complicated by the many environmental factors affecting the growth and production of living organisms. The financial constraint that equipment must repay costs through improved economic productivity must be considered by the designer. The engineer must balance the economic costs of modifying the environment against the economic losses of a plant or animal in a less-than-ideal environment.

Thus, the design of plant and animal housing is affected by (1) economics, (2) concern for both workers and the care and well-being of animals, and (3) regulations on pollution, sanitation, and health assurance.

DESIGN FOR ANIMAL ENVIRONMENTS

Typical animal production plants modify the environment, to some degree, by housing or sheltering animals year-round or for parts of a year. The degree of modification is generally based on the expected increase in production. Animal sensible heat and moisture production data, combined with information on the effects of environment on growth, productivity, and reproduction, help designers select optimal equipment (Chapter 10 of the 2001 *ASHRAE Handbook—Fundamentals*). Detailed information is available in a series of handbooks published by the MidWest Plan Service. These include *Mechanical Ventilating Systems for Livestock Housing* (MWPS 1990), *Natural Ventilating Systems for Livestock Housing and Heating* (MWPS 1989), and *Cooling and Tempering Air for Livestock Housing* (MWPS 1990). ASAE *Monograph* No. 6, Ventilation of Agricultural Structures (Hellickson and Walter 1983), also gives more detailed information.

Design Approach

Environmental control systems are typically designed to maintain thermal and air quality conditions within an acceptable range and as near the ideal for optimal animal performance as is practicable. Equipment is usually sized assuming steady-state energy and mass conservation equations. Experimental measurements confirm that heat and moisture production by animals is not constant and that there may be important thermal capacitance effects in livestock buildings. Nevertheless, for most design situations, the steady-state equations are acceptable.

Achieving the appropriate fresh air exchange rate and establishing the proper distribution within the room are generally the two most important design considerations. The optimal ventilation rate is selected according to the ventilation rate logic curve (Figure 1).

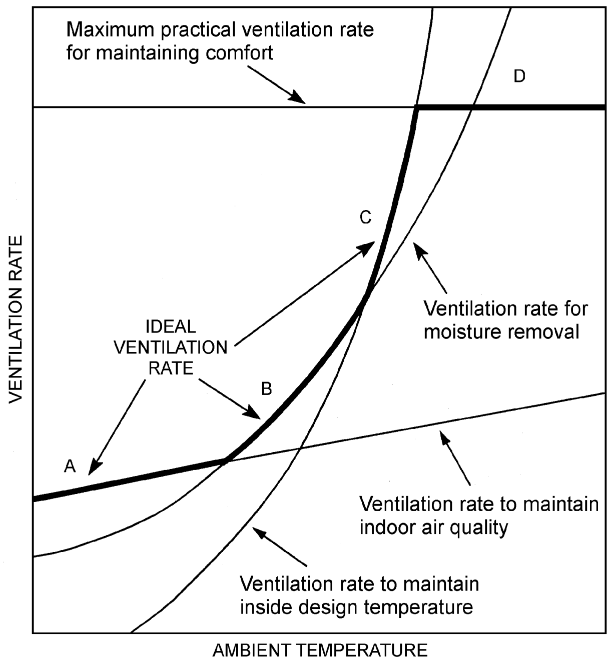

Fig. 1 Logic for Selecting the Appropriate Ventilation Rate in Livestock Buildings
(Adapted from Christianson and Fehr 1983)

During the coldest weather, the ideal ventilation rate is that required to maintain indoor relative humidity at or below the maximum desired, and air contaminant concentrations within acceptable ranges (Rates A and B in Figure 1). Supplemental heating is often required to prevent the temperature from dropping below optimal levels.

In milder weather, the ventilation rate required for maintaining optimal room air temperature is greater than that required for moisture and air quality control (Rates C and D in Figure 1). In hot weather, the ventilation rate is chosen to minimize the temperature rise above ambient and to provide optimal air movement over animals. Cooling is sometimes used in hot weather. The maximum rate (D) is often set at 60 air changes per hour as a practical maximum.

Temperature Control

The temperature within an animal structure is computed from the sensible heat balance of the system, usually disregarding transient effects. Nonstandard buildings with low airflow rates and/or large thermal mass may require transient analysis. Steady-state

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heat transfer through walls, ceiling or roof, and ground is calculated as presented in Chapter 25 of the 2001 *ASHRAE Handbook—Fundamentals*.

Mature animals typically produce more heat per of unit floor area than do young stock. Chapter 10 of the 2001 *ASHRAE Handbook—Fundamentals* presents estimates of animal heat loads. Lighting and equipment heat loads are estimated from power ratings and operating times. Typically, the designer selects indoor and outdoor design temperatures and calculates the ventilation rate to maintain the temperature difference. Outdoor design temperatures are given in Chapter 27 of the 2001 *ASHRAE Handbook—Fundamentals*. The section on Recommended Practices by Species in this chapter presents indoor design temperature values for various livestock.

Moisture Control

Moisture loads produced in an animal building may be calculated from data in Chapter 10 of the 2001 *ASHRAE Handbook—Fundamentals*. The mass of water vapor produced is estimated by dividing the animal latent heat production by the latent heat of vaporization of water at animal body temperature. Water spilled and evaporation of fecal water must be included in the estimates of latent heat production within the building. The amount of water vapor removed by ventilation from a totally slatted (manure storage beneath floor) swine facility may be up to 40% less than the amount removed from a solid concrete floor. If the floor is partially slatted, the 40% maximum reduction is decreased in proportion to the percentage of the floor that is slatted.

The ventilation should remove enough moisture to prevent condensation but should not reduce the relative humidity so low (less than 40%) as to create dusty conditions. Design indoor relative humidity for winter ventilation is usually between 70 and 80%. The walls should have sufficient insulation to prevent surface condensation at 80% rh inside.

During cold weather, the ventilation needed for moisture control usually exceeds that needed to control temperature. Minimum ventilation must always be provided to remove animal moisture. Up to a full day of high humidity may be permitted during extreme cold periods when normal ventilation rates could cause an excessive heating demand. Humidity level is not normally the controlling factor in mild or hot weather.

Air Quality Control

Contaminants. The most common and prevalent air contaminant in animal buildings is particulates. In animal buildings, particulates originate mainly from the feed, litter, fecal materials, and animals. Particulates include solid particles, liquid droplets, microorganisms, and moisture, and can be deposited deep within the respiratory system. Particulates carry the allergens which cause discomfort and health problems for workers in laboratory rodent facilities. They also carry much of the odors in animal facilities, and can carry the odors for long distances from the facilities. Consequently, particulates pose major problems for animals, workers, and neighbors. Particulate levels in swine buildings have been measured to range from 1 to 15 mg/m^3. Dust has not been a major problem in dairy buildings; one two-year study found an average of only 0.5 mg/m^3 in a naturally ventilated dairy barn. Poultry building dust levels average around 2 to 7 mg/m^3, but levels up to 18 to 29 mg/m^3 have been measured during high activity periods.

The most common gas contaminants are ammonia, hydrogen sulfide, other odorous compounds, carbon dioxide, and carbon monoxide. High moisture levels can also aggravate other contaminant problems. Ammonia, which results from the decomposition of manure, is the most important chronically present contaminant gas. Typical ammonia levels measured have been 7 to 37 mg/m^3 in poultry units, 0 to 15 mg/m^3 in cattle buildings, 4 to 22 mg/m^3 in swine units with liquid manure systems, and 7 to 37 mg/m^3 in swine units with solid floors (Ni et al. 1998a). Up to 150 mg/m^3 have been measured in swine units in winter. Ammonia should be maintained below 18 mg/m^3 and, ideally, below 7 mg/m^3.

Zhang et al. (1992) and Maghirang et al. (1995) found ammonia levels in laboratory animal rooms to be negligible, but concentrations could reach 45 mg/m^3 in cages. Weiss et al. (1991) found ammonia levels in rat cages of up to 260 mg/m^3 with four male rats per cage and 50 mg/m^3 with four female rats per cage. Hasenau et al. (1993) found that ammonia levels varied widely among various mouse microisolation cages; ammonia ranged from negligible to 380 mg/m^3 nine days after cleaning the cage.

Hydrogen sulfide, a by-product of the microbial decomposition of stored manure, is the most important acute gas contaminant. During normal operation, hydrogen sulfide concentration is usually insignificant (i.e., below 1 mg/m^3). A typical level of hydrogen sulfide in swine buildings is around 200 to 500 μg/m^3 (Ni et al. 1998b). However, levels can reach 280 to 460 mg/m^3, and possibly up to 1.4 to 11 g/m^3 during in-building manure agitation.

Odors from animal facilities are becoming an increasing concern, both in the facilities and in the surrounding areas. Odors result from both gases and particulates; particulates are of primary concern since odorous gases can be quickly diluted below odor threshold concentrations in typical weather conditions, while particulates can retain odor for long periods. Methods that control particulate and odorous gas concentrations in the air will reduce odors, but controlling odor generation at the source appears to be the most promising method of odor control.

Barber et al. (1993), reporting on 173 pig buildings, found that carbon dioxide concentrations were below 5400 mg/m^3 in nearly all instances when the external temperature was above 0°C but almost always above 5400 mg/m^3 when the temperature was below 0°C. The report indicated that there was a very high penalty in heating cost in cold climates if the maximum-allowed carbon dioxide concentration was less than 9000 mg/m^3. Air quality control based on carbon dioxide concentrations was suggested by Donham et al. (1989). They suggested a carbon dioxide concentration of 2770 mg/m^3 as a threshold level, above which symptoms of respiratory disorders occurred in a population of swine building workers. For other industries, a carbon dioxide concentration of 9000 mg/m^3 is suggested as the time-weighted threshold limit value for 8 h of exposure (ACGIH 1998).

Other gas contaminants can also be important. Carbon monoxide from improperly operating unvented space heaters sometimes reaches problem levels. Methane is another occasional concern.

Control Methods. Three standard methods used to control air contaminant levels in animal facilities are

1. Reduce contaminant production at the source.
2. Remove contaminants from the air.
3. Reduce gas contaminant concentration by dilution (ventilation).

The first line of defense is to reduce release of contaminants from the source, or to at least intercept and remove them before they reach the workers and animals. Animal feces and urine are the largest sources of contaminants; but feed, litter, and the animals themselves are also a major source of contaminants, especially particulates. Successful operations effectively collect and remove all manure from the building within three days, before it decomposes sufficiently to produce large quantities of contaminants. Removing ventilation air uniformly from manure storage or collection areas helps remove contaminants before they reach animal or worker areas.

Ammonia production can be minimized by removing wastes from the room and keeping floor surfaces or bedding dry. Immediately covering manure solids in gutters and pits with water also reduces ammonia, which is highly soluble in water. Since adverse effects of hydrogen sulfide on production begin to occur at 30 mg/m^3, ventilation systems should be designed to maintain hydrogen sulfide levels below 30 mg/m^3 during agitation. When manure is agitated and removed from the storage, the building should be well ventilated and all animals and occupants evacuated due to potentially fatal concentrations of gases.

For laboratory animals, changing the bedding frequently and keeping the bedding dry with lower relative humidities and appropriate cage ventilation can reduce ammonia release. Individually ventilated laboratory animal cages or the placement of cages in mass air displacement units reduce contaminant production by keeping litter drier. Using localized contaminant containment work stations for dust-producing tasks such as cage-changing may also help. For poultry or laboratory animals, the relative humidity of air surrounding the litter should be kept between 50% and 75% to reduce particulate and gas contaminant release. Relative humidities between 40% and 75% also reduce the viability of pathogens in the air. A moisture content of 25 to 30% (wet basis) in the litter or bedding, keeps dust to a minimum. Adding 0.5 to 2% of edible oil or fat can significantly reduce dust emission from the feed. Respirable dust (smaller than 10 μm), which is most harmful to the health and comfort of personnel and animals, is primarily from feces, animal skins, and dead microorganisms. Respirable dust concentration should be kept below 0.23 mg/m^3. Some dust control technologies are available. For example, sprinkling oil at 5 mL/m^2 of floor area per day can reduce dust concentration by more that 80%. High animal activity levels release large quantities of particulates into the air, so management strategies to reduce agitation of animals are helpful.

Methods of removing contaminants from the air are essentially limited to particulate removal since gas removal methods are often too costly for animal facilities. Some animal workers wear personal protection devices (appropriate masks) to reduce inhaled particulates. Room air filters reduce animal disease problems, but they have not proven practical for large animal facilities due to the large quantity of particulates and the difficulty in drawing the particulates from the room and through a filter. Air scrubbers have the capability to remove gases and particulates, but the initial cost and maintenance make them impractical. Aerodynamic centrifugation is showing promise for removing the small particulates found in animal buildings.

Ventilation is the most prevalent method used to control gas contaminant levels in animal facilities. It is reasonably effective in removing gases, but not as effective in removing particulates. Pockets in a room with high concentrations of gas contaminants are common. These polluted pockets occur in dead air spots or near large contaminant sources. Providing high levels of ventilation can be costly in winter, can create drafts on the animals, and can increase the release of gas contaminants by increasing air velocity across the source.

Disease Control

Airborne microbes can transfer disease-causing organisms among animals. For some situations, typically with young animals where there are low-level infections, it is important to minimize air mixing among animal groups. It is especially important to minimize air exchange between different animal rooms, so buildings need to be fairly airtight.

Poor thermal environments and air contaminants can increase stress on the animals, which can make them more susceptible to disease. Therefore, a good environmental control system is important for disease control.

Air Distribution

Air speed should be maintained below 0.25 m/s for most animal species in both cold and mild weather. Animal sensitivities to draft are comparable to those of humans, although some animals are more sensitive at different stages. Riskowski and Bundy (1988) documented that air velocities for optimal rates of gain and feed efficiencies can be below 0.13 m/s for young pigs at thermoneutral conditions.

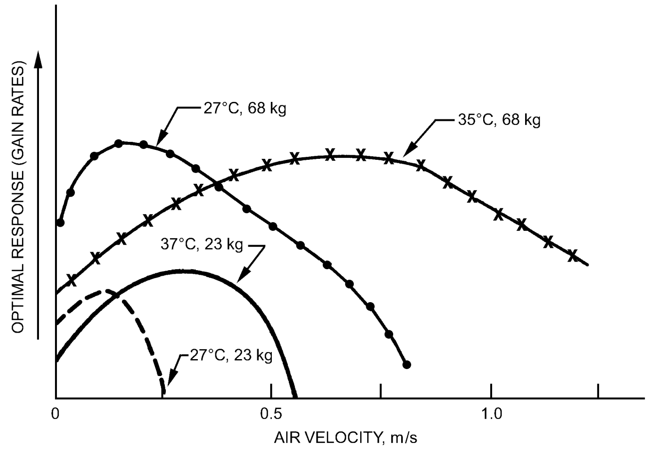

Fig. 2 Response of Swine to Air Velocity

Increased air movement during hot weather increases growth rates and improves heat tolerance. There are conflicting and limited data defining optimal air velocity in hot weather. Bond et al. (1965) and Riskowski and Bundy (1988) determined that both young and mature swine perform best when air speed is less than 1 m/s (Figure 2). Mount and Start (1980) did not observe performance penalties at air speeds increased to a maximum of 0.76 m/s.

Degree of Shelter

Livestock, especially young animals, need some protection from adverse climates. On the open range, mature cattle and sheep need protection during severe winter conditions. In winter, dairy cattle and swine may be protected from precipitation and wind with a three-sided, roofed shelter open on the leeward side. The windward side should also have approximately 10% of the wall surface area open to prevent a negative pressure inside the shelter; this pressure could cause rain and snow to be drawn into the building on the leeward side. Such shelters do not protect against extreme temperature or high humidity.

In warmer climates, shades often provide adequate shelter, especially for large, mature animals such as dairy cows. Shades are commonly used in Arizona; research in Florida has shown an approximate 10% increase in milk production and a 75% increase in conception efficiency for shaded versus unshaded cows. The benefit of shades has not been documented for areas with less severe summer temperatures. Although shades for beef cattle are also common practice in the southwest, beef cattle are somewhat less susceptible to heat stress, and extensive comparisons of various shade types in Florida have detected little or no differences in daily mass gain or feed conversion.

The energy exchange between an animal and various areas of the environment is illustrated in Figure 3. A well-designed shade makes maximum use of radiant heat sinks, such as the cold sky, and gives maximum protection from direct solar radiation and high surface temperature under the shade. Good design considers geometric orientation and material selection, including roof surface treatment and insulation material on the lower surface.

An ideal shade has a top surface that is highly reflective to solar energy and a lower surface that is highly absorptive to solar radiation reflected from the ground. A white-painted upper surface reflects solar radiation, yet emits infrared energy better than aluminum. The undersurface should be painted a dark color to prevent multiple reflection of shortwave energy onto animals under the shade.

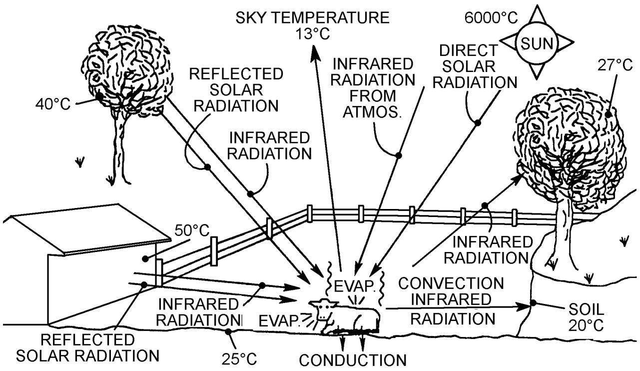

Fig. 3 Energy Exchange Between a Farm Animal and Its Surroundings in a Hot Environment

COOLING AND HEATING

Air Velocity

Increasing air velocity helps to facilitate the cooling of mature animals. It is especially beneficial when combined with skin wetting evaporative cooling. Mature swine benefit most with air velocities up to 1 m/s; cattle around 1.5 m/s; and poultry around 3 m/s. Air velocity can be increased with air circulation fans that blows air horizontally in circular patterns around the room, paddle fans that blow air downward, or tunnel cooling that moves air horizontally along the length of the building.

Evaporative Cooling

Supplemental cooling of animals in intensive housing conditions may be necessary during heat waves to prevent heat prostration, mortality, or serious losses in production and reproduction. Evaporative cooling, which may reduce ventilation air to 27°C or lower in most of the United States, is popular for poultry houses, and is sometimes used for swine and dairy housing.

Evaporative cooling is well suited to animal housing because the high air exchange rates effectively remove odors and ammonia, and increase air movement for convective heat relief. Initial cost, operating expense, and maintenance problems are all relatively low compared to other types of cooling systems. Evaporative cooling works best in areas with low relative humidity, but significant benefits can be obtained even in the humid southeastern United States.

Design. The pad area should be sized to maintain air velocities between 1.0 and 1.4 m/s through the pads. For most pad systems, these velocities produce evaporative efficiencies between 75 and 85%; they also increase pressures against the ventilating fans from 10 to 30 Pa, depending on the pad design.

The building and pad system must be airtight because air leaks due to the negative pressure ventilation will reduce the airflow through the pads, and hence reduce the cooling effectiveness.

The most serious problem encountered with evaporative pads for agricultural applications is clogging by dust and other airborne particles. Whenever possible, fans should exhaust away from pads on adjacent buildings. Regular preventive maintenance is essential. Water bleed-off and the addition of algaecides to the water are recommended. When pads are not used in cool weather, they should be sealed to prevent dusty inside air from exhausting through them.

High-pressure fogging with water pressure of 3.5 MPa is preferred to pad coolers for cooling the air in broiler houses with built-up litter. The high pressure creates a fine aerosol, causing minimal litter wetting. Timers and/or thermostats control the cooling. Evaporative efficiency and installation cost are about one-half those of a well-designed evaporative pad. Foggers can also be used with naturally ventilated, open-sided housing. Low-pressure systems are not recommended for poultry, but may be used during emergencies.

Nozzles that produce water mist or spray droplets to wet animals directly are used extensively during hot weather in swine confinement facilities with solid concrete or slatted floors. Currently, misting or sprinkling systems with larger droplets that directly wet the skin surface of the animals (not merely the outer portion of the hair coat) are preferred. Timers that operate periodically, (e.g., 2 to 3 min on a 15 to 20 min cycle) help to conserve water.

Mechanical Refrigeration

Mechanical refrigeration can be designed for effective animal cooling, but it is considered uneconomical for most production animals. Air-conditioning loads for dairy housing may require 2.5 kW or more per cow. Recirculation of refrigeration air is usually not feasible due to high contaminant loads in the air in the animal housing. Sometimes, zone cooling of individual animals is used instead of whole-room cooling, particularly in swine farrowing houses where a lower air temperature is needed for sows than for unweaned piglets. It is also beneficial for swine boars and gestating sows. Refrigerated air, 10 to 20 K below ambient temperature, is supplied through insulated ducts directly to the head and face of the animal. Air delivery rates are typically 10 to 20 L/s per animal for snout cooling, and 30 to 40 L/s per sow for zone cooling.

Earth Tubes

Some livestock facilities obtain cooling in summer and heating in winter by drawing ventilation air through tubing buried 2 to 4 m below grade. These systems are most practical in the north central United States for animals that benefit from both cooling in summer and heating in winter.

Cooling and Tempering Air for Livestock Housing (MWPS 1990) details design procedures for this method. A typical design uses 15 to 50 m of 200 mm diameter pipe to provide 150 L/s of tempered air. Soil type and moisture, pipe depth, airflow, climate, and other factors affect the efficiency of buried pipe heat exchangers. The pipes must slope to drain condensation, and must not have dips that could plug with condensation.

Heat Exchangers

Ventilation accounts for 70 to 90% of the heat losses in typical livestock facilities during winter. Heat exchangers can reclaim some of the heat lost with the exhaust ventilating air. However, predicting fuel savings based on savings obtained during the coldest periods will overestimate yearly savings from a heat exchanger. Estimates of energy savings based on air enthalpy can improve the accuracy of the predictions.

Heat exchanger design must address the problems of condensate freezing and/or dust accumulation on the heat exchanging surfaces. If unresolved, these problems result in either reduced efficiency and/or the inconvenience of frequent cleaning.

Supplemental Heating

For poultry with a mass of 1.5 kg or more, for pigs heavier than 23 kg, and for other large animals such as dairy cows, the body heat of the animals at recommended space allocations is usually sufficient to maintain moderate temperatures (i.e., above 10°C) in a well-insulated structure. Combustion-type heaters are used to supplement heat for baby chicks and pigs. Supplemental heating also increases the moisture-holding capacity of the air, which reduces the quantity of air required for removal of moisture. Various types of heating equipment

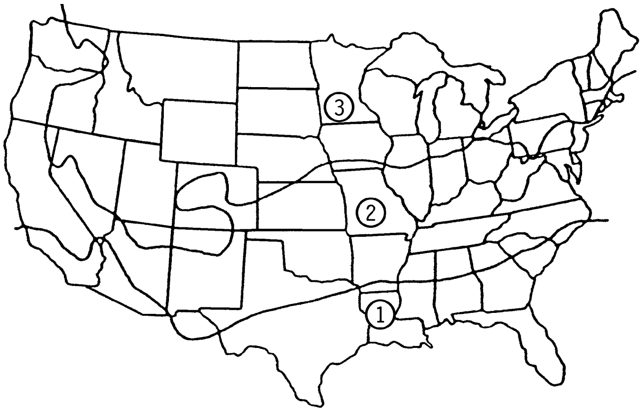

Fig. 4 Climatic Zones
(Reprinted with permission from ASAE *Standard* S401.2)

Table 1 Minimum Recommended Overall Coefficients of Heat Transmission *U* for Insulated Assemblies[a,b]

Climatic Zone[d]	Recommended Minimum *U*, W/(m²·K)[c]					
	Cold		Modified Environment		Supplementally Heated	
	Walls	Ceiling	Walls	Ceiling	Walls	Ceiling
1	—	0.91[e]	0.91[e]	0.40	0.40	0.26
2	—	0.91	0.91	0.33	0.40	0.23
3	—	0.91	0.48	0.23	0.29	0.17

[a]Use assembly U-factors that include framing effects, air spaces, air films, linings, and sidings. Determine assembly U-factors by testing the full assembly in accordance with ASTM C236 or C976 or calculate by the procedures presented in the 1997 *ASHRAE Handbook—Fundamentals.*
[b]Values shown do not represent the values necessary to provide a heat balance between heat produced by products or animals and heat transferred through the building.
[c]Current practice for poultry grow-out buildings uses a *U* of 0.63 to 0.81 W/(m²·K) in the roof and walls.
[d]Refer to Figure 4.
[e]Where ambient temperature and radiant heat load are severe, use $U = 0.48$ W/(m²·K).

may be included in ventilation, but they need to perform well in dusty and corrosive atmospheres.

Insulation Requirements

The amount of building insulation required depends on climate, animal space allocations, and animal heat and moisture production. Refer to Figure 4 and Table 1 for selecting insulation levels. In warm weather, ventilation between the roof and insulation helps reduce the radiant heat load from the ceiling. Insulation in warm climates can be more important for reducing radiant heat loads in summer than reducing building heat loss in winter.

Cold buildings have indoor conditions about the same as outside conditions. Examples are free-stall barns and open-front livestock buildings. Minimum insulation is frequently recommended in the roofs of these buildings to reduce solar heat gain in summer and to reduce condensation in winter.

Modified environment buildings rely on insulation, natural ventilation, and animal heat to remove moisture and to maintain the inside within a specified temperature range. Examples are warm free-stall barns, poultry production buildings, and swine finishing units.

Supplementary heated buildings require insulation, ventilation, and extra heat to maintain the desired inside temperature and humidity. Examples are swine farrowing and nursery buildings.

VENTILATION

Mechanical Ventilation

Mechanical ventilation uses fans to create a static pressure difference between the inside and outside of a building. Farm buildings use either positive pressure, with fans forcing air into a building, or negative pressure, with exhaust fans. Some ventilation systems use a combination of positive pressure to introduce air into a building and separate fans to remove air. These zero-pressure systems are particularly appropriate for heat exchangers.

Positive Pressure Ventilation. Fans blow outside air into the ventilated space, forcing humid air out through any planned outlets and through leaks in walls and ceilings. If vapor barriers are not complete, moisture condensation will occur within the walls and ceiling during cold weather. Condensation causes deterioration of building materials and reduces insulation effectiveness. The energy used by fan motors and rejected as heat is added to the building—an advantage in winter but a disadvantage in summer.

Negative Pressure Ventilation. Fans exhaust air from the ventilated space while drawing outside air in through planned inlets and leaks in walls, in ceilings, and around doors and windows. Air distribution in negative pressure ventilation is often less complex and costly than positive or neutral pressure systems. Simple openings and baffled slots in walls control and distribute air in the building. However, at low airflow rates, negative pressure ventilation may not distribute air uniformly due to air leaks and wind pressure effects. Supplemental air mixing may be necessary.

Allowances should be made for reduced fan performance due to dust, guards, and corrosion of louver joints (Person et al. 1979). Totally enclosed fan motors are protected from exhaust air contaminants and humidity. Periodic cleaning helps prevent overheating. Negative pressure ventilation is more commonly used than positive pressure ventilation.

Ventilation should always be designed so that manure gases are not drawn into the building from manure storages connected to the building by underground pipes or channels.

Neutral Pressure Ventilation. Neutral pressure (push-pull) ventilation typically use supply fans to distribute air down a distribution duct to room inlets and exhaust fans to remove air from the room. Supply and exhaust fan capacities should be matched.

Neutral pressure systems are often more expensive, but they achieve better control of the air. They are less susceptible to wind effects and to building leakage than positive or negative pressure systems. Neutral pressure systems are most frequently used for young stock and for animals most sensitive to environmental conditions, primarily where cold weather is a concern.

Natural Ventilation

Either natural or mechanical ventilation is used to modify environments in livestock shelters. Natural ventilation is most common for mature animal housing, such as free-stall dairy, poultry growing, and swine finishing houses. Natural ventilation depends on pressure differences caused by wind and temperature differences. Well-designed natural ventilation keeps temperatures reasonably stable, if automatic controls regulate ventilation openings. Usually, a design includes an open ridge (with or without a rain cover) and openable sidewalls, which should cover at least 50% of the wall for summer operation. Ridge openings are about 17 mm wide for each metre of house width, with a minimum ridge width of 150 mm. to avoid freezing problems in cold climates. Upstand baffles on each side of the ridge opening greatly increase airflow (Riskowski et al. 1998). Small screens and square edges around sidewall openings can significantly reduce airflow through vents.

Openings can be adjusted automatically, with control based on air temperature. Some designs, referred to as flex housing, include a combination of mechanical and natural ventilation usually dictated by outside air temperature and/or the amount of ventilation required.

VENTILATION MANAGEMENT

Air Distribution

Pressure differences across walls and inlet or fan openings are usually maintained between 10 and 15 Pa. (The exhaust fans are usually sized to provide proper ventilation at pressures up to 30 Pa to compensate for wind effects.) This pressure difference creates inlet velocities of 3 to 5 m/s, sufficient for effective air mixing, but low enough to cause only a small reduction in fan capacity. A properly planned inlet system distributes fresh air equally throughout the building. Negative pressure ventilation that relies on cracks around doors and windows does not distribute fresh air effectively. Inlets require adjustment, since winter airflow rates are typically less than 10% of summer rates. Automatic controllers and inlets are available to regulate inlet areas.

Positive pressure ventilation, with fans connected directly to perforated air distribution tubes, may combine heating, circulation, and ventilation in one system. Air distribution tubes or ducts connected to circulating fans are sometimes used to mix the air in negative pressure ventilation. Detailed design procedures for perforated ventilation tubes are described by Zhang (1994). However, dust in the ducts is of concern when air is recirculated, particularly when cold incoming air condenses moisture in the tubes.

Inlet Design. Inlet location and size most critically affect air distribution within a building. Continuous or intermittent inlets can be placed along the entire length of one or both outside walls. Building widths narrower than 6 m may need only a single inlet along one wall. The total inlet area may be calculated by the system characteristic technique, which follows. Because the distribution of the inlet area is based on the geometry and size of the building, specific recommendations are difficult.

System Characteristic Technique. This technique determines the operating points for the ventilation rate and pressure difference across inlets. Fan airflow rate as a function of pressure difference across the fan should be available from the manufacturer. Allowances must be made for additional pressure losses from fan shutters or other devices such as light restriction systems or cooling pads.

Inlet flow characteristics are available for hinged baffle and center-ceiling flat baffle slotted inlets (Figure 5). Airflow rates can be calculated for the baffles in Figure 5 by the following:

For Case A:

$$Q = 1.1\ Wp^{0.5} \tag{1}$$

For Case B:

$$Q = 0.71\ Wp^{0.5} \tag{2}$$

For Case C (Total airflow from sum of both sides):

$$Q = 1.3\ Wp^{0.5}(D/T)^{0.08}e^{(-0.867\,W/T)} \tag{3}$$

where

Q = airflow rate, L/s per metre length of slot opening
W = slot width, mm
p = pressure difference across the inlet, Pa
D = baffle width, mm
T = width of slot in ceiling, mm

Zhang and Barber (1995) measured infiltration rates of five rooms in a newly built swine building at 0.6 L/s per square metre of surface area at 20 Pa. Surface area included the area of walls and ceiling enclosing the room. It is important to include this infiltration rate into the ventilation design and management. For example, at 0.6 L/s per square metre of surface area, the infiltration represents 1.4 air changes per hour. In the heating season, the minimum ventilation is usually about 3 air changes per hour. Thus, large infiltration rates greatly reduce the airflow from the controlled inlet and adversely affect the air distribution.

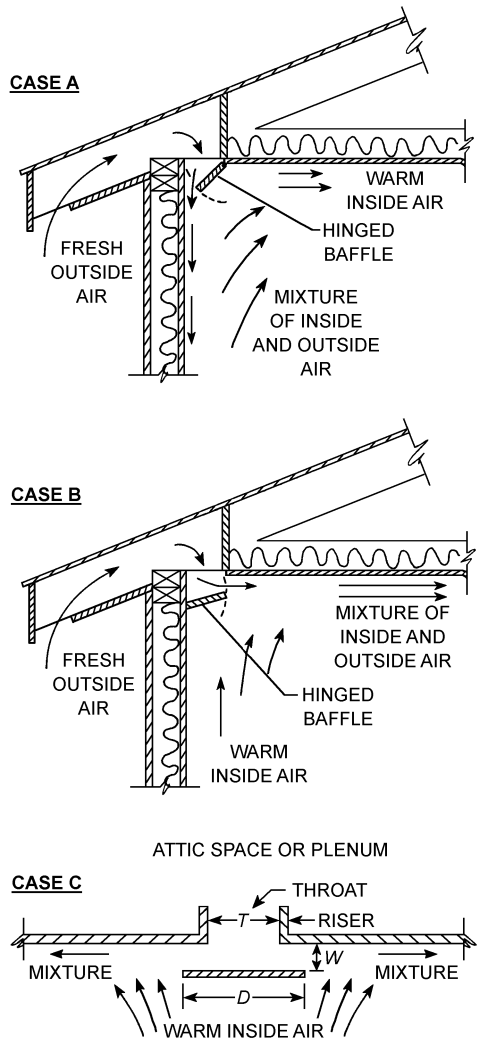

Fig. 5 Typical Livestock Building Inlet Configurations

Room Air Velocity. The average air velocity inside a slot ventilated structure relates to the inlet air velocity, inlet slot width (or equivalent continuous length for boxed inlets), building width, and ceiling height. Estimates of air velocity within a barn, based on air exchange rates, may be very low due to the effects of jet velocity and recirculation. Conditions are usually partially turbulent, and there is no reliable way to predict room air velocity at animal level. General design guidelines keep the throw distance less than 6 m from slots and less than 3 m from perforated tubes.

Fans

Fans should not exhaust against prevailing winds, especially for cold-weather ventilation. If structural or other factors require installing fans on the windward side, fans rated to deliver the required capacity against at least 30 Pa static pressure and with a relatively flat power curve should be selected. The fan motor should withstand a wind velocity of 50 km/h, equivalent to a static pressure of 100 Pa, without overloading beyond its service factor. Wind hoods on the fans or windbreak fences reduce the effects of wind.

Third-party test data should be used to obtain fan performance and energy efficiencies for fan selection (BESS Lab 1997). Fans should be tested with all accessories (such as louvers, guards, and hoods) in place, just as they will be installed in the building. The accessories have a major effect on fan performance.

Flow Control. Since the numbers and size of livestock and climatic conditions vary, means to modulate ventilation rates are often required beyond the conventional off/on thermostat switch. The minimum ventilation rate to remove moisture, reduce air contaminant concentrations, and keep water from freezing should always be provided. Methods of modulating ventilation rates include: (1) intermittent fan operation—fans operate for a percentage of the time controlled by a percentage timer with a 10 min cycle; (2) staging of fans using multiple units or fans with high/low-exhaust capability; (3) the use of multispeed fans—larger fans (400 W and up) with two flow rates, the lower being about 60% of the maximum rate; and (4) the use of variable-speed fans—split-capacitor motors designed to modulate fan speed smoothly from maximum down to 10 to 20% of the maximum rate (the controller is usually thermostatically adjusted).

Generally, fans are spaced uniformly along the winter leeward side of a building. Maximum distance between fans is 35 to 40 m. Fans may be grouped in a bank if this range is not exceeded. In housing with side curtains, exhaust fans that can be reversed or removed and placed inside the building in the summer are sometimes installed to increase air movement in combination with doors, walls, or windows being opened for natural ventilation.

Thermostats

Thermostats should be placed where they respond to a representative temperature as sensed by the animals. Thermostats need protection and should be placed to prevent potential physical or moisture damage (i.e., away from animals, ventilation inlets, water pipes, lights, heater exhausts, outside walls, or any other objects that will unduly affect performance). Thermostats also require periodic adjustment based on accurate thermometer readings taken in the immediate proximity of the animal.

Emergency Warning

Animals housed in a high-density, mechanically controlled environment are subject to considerable risk of heat prostration if a failure of power or ventilation equipment occurs. To reduce this danger, an alarm and an automatic standby electric generator are highly recommended. Many alarms will detect failure of the ventilation. These alarms range from inexpensive power-off alarms to alarms that sense temperature extremes and certain gases. Automatic telephone-dialing systems are effective as alarms and are relatively inexpensive. Building designs that allow some side wall panels (e.g., 25% of wall area) to be removed for emergency situations are also recommended.

RECOMMENDED PRACTICES BY SPECIES

Mature animals readily adapt to a broad range of temperatures, but efficiency of production varies. Younger animals are more temperature sensitive. Figure 6 illustrates animal production response to temperature.

Relative humidity has not been shown to influence animal performance, except when accompanied by thermal stress. Relative humidity consistently below 40% may contribute to excessive dustiness; above 80%, it may increase building and equipment deterioration. Disease pathogens also appear to be more viable at either low or high humidity. Relative humidity has a major influence on the effectiveness of skin-wetting cooling methods.

Dairy Cattle

Dairy cattle shelters include confinement stall barns, free stalls, and loose housing. In a stall barn, cattle are usually confined to stalls approximately 1.2 m wide, where all chores, including milking and feeding, are conducted. Such a structure requires environmental modification, primarily through ventilation. Total space requirements are 5 to 7 m^2 per cow. In free-stall housing, cattle are not confined to stalls but can move freely. Space requirements per cow are 7 to 9 m^2. In loose housing, cattle are free to move within a fenced lot containing resting and feeding areas. Space required in sheltered loose housing is similar to that in free-stall housing. The shelters for resting and feeding areas are generally open-sided and require no air conditioning or mechanical ventilation, but supplemental air mixing is often beneficial during warm weather. The milking area is in a separate area or facility and may be fully or partially enclosed, thus requiring some ventilation.

For dairy cattle, climate requirements for minimal economic loss are broad, and range from 2 to 24°C with 40 to 80% rh. Below 2°C, production efficiency declines and management problems increase. However, the effect of low temperature on milk production is not as extreme as are high temperatures, where evaporative coolers or other cooling methods may be warranted.

Ventilation Rates for Each 500 kg Cow

Winter	Spring/Fall	Summer
17 to 22 L/s	67 to 90 L/s	110 to 220 L/s

Required ventilation rates depend on specific thermal characteristics of individual buildings and internal heating load. The relative humidity should be maintained between 50 and 80%.

Both loose housing and stall barns require an additional milk room to cool and hold the milk. Sanitation codes for milk production contain minimum ventilation requirements. The market being supplied should be consulted for all applicable codes. Some state codes require positive pressure ventilation of milk rooms. Milk rooms are usually ventilated with fans at rates of 4 to 10 air changes per hour to satisfy requirements of local milk codes and to remove heat from milk coolers. Most milk codes require ventilation in the passageway (if any) between the milking area and the milk room.

Beef Cattle

Beef cattle ventilation requirements are similar to those of dairy cattle on a unit mass basis. Beef production facilities often provide only shade and wind breaks.

Swine

Swine housing can be grouped into four general classifications:

1. Farrowing pigs, from birth to 14 kg, and sows
2. Nursery pigs, from 14 to 34 kg
3. Growing/finishing pigs, from 34 kg to market size
4. Breeding and gestation

In farrowing barns, two environments must be provided: one for sows and one for piglets. Because each requires a different temperature, zone heating and/or cooling is used. The environment within the nursery is similar to that within the farrowing barn for piglets. The requirements for growing barns and breeding stock housing are similar.

Currently recommended practices for **farrowing houses**:

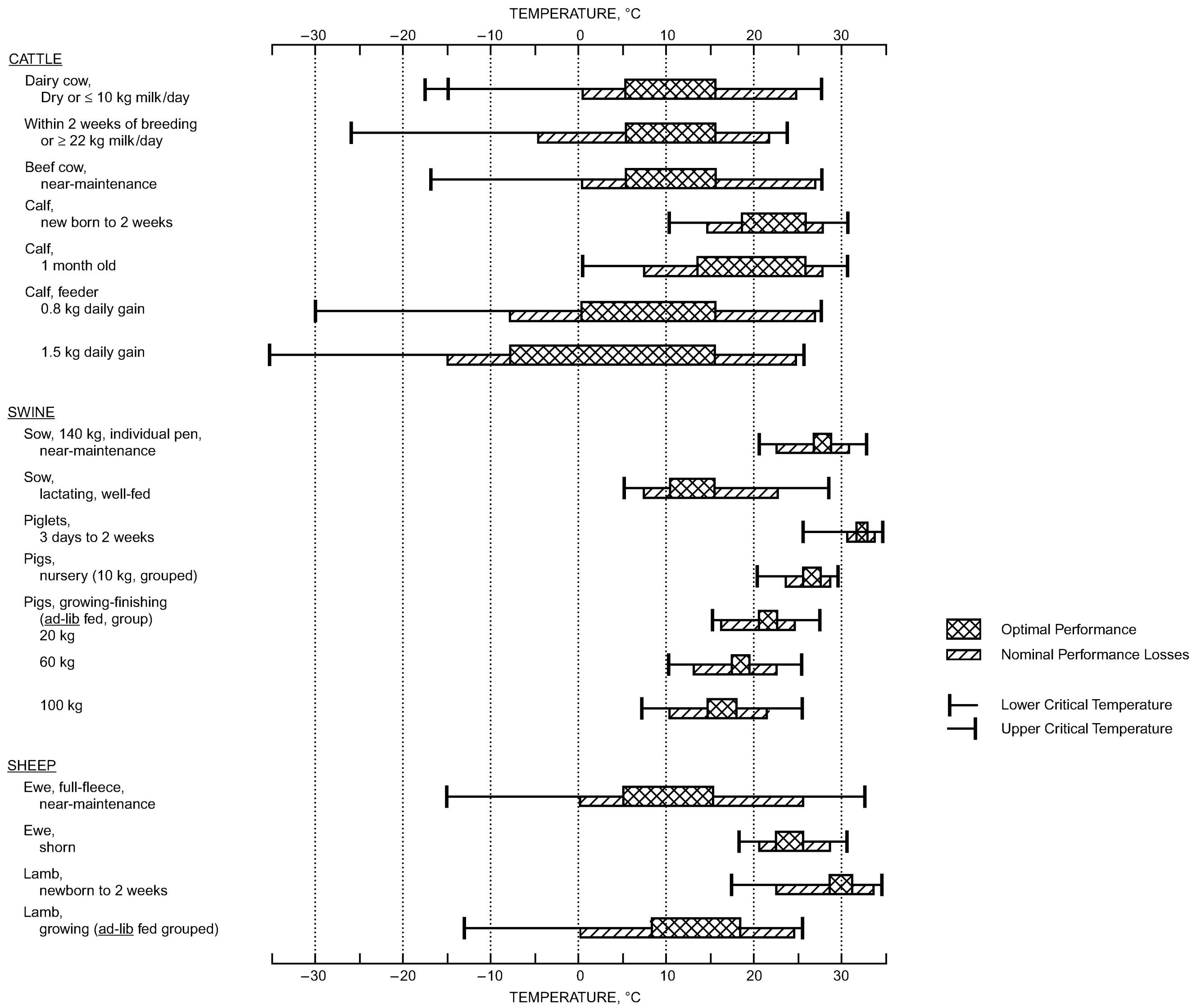

Fig. 6 Critical Ambient Temperatures and Temperature Zone for Optimum Performance and Nominal Performance Loss in Farm Animals
(Hahn 1985, in *Stress Physiology in Livestock*, Vol. II, CRC Press)

- Temperature: 10 to 20°C, with small areas for piglets warmed to 28 to 32°C by means of brooders, heat lamps, or floor heat. Avoid cold drafts and extreme temperatures. Hovers are sometimes used. Provide supplemental cooling for sows (usually drippers or zone cooling) in extreme heat.
- Relative humidity: Up to 70% maximum
- Ventilation rate: 10 to 240 L/s per sow and litter (about 180 kg total mass). The low rate is for winter; the high rate is for summer temperature control.
- Space: 3.25 m^2 per sow and litter (stall); 6.0 m^2 per sow and litter (pens)

Recommendations for **nursery barns**:

- Temperature:
  27°C for first week after weaning. Lower room temperature 1.5 K per week to 21°C. Provide warm, draft-free floors. Provide supplemental cooling for extreme heat (temperatures 30°C and above).
- Ventilation rate:
  1 to 12 L/s per pig, 5.5 to 14 kg each
  1.5 to 18 L/s per pig, 6 to 36 kg each
- Space:
  0.19 to 0.23 m^2 per pig, 5.5 to 14 kg each
  0.28 to 0.37 m^2 per pig, 6 to 14 kg each

Recommendations for **growing** and **gestation barns**:

- Temperature:
  13 to 22°C preferred. Provide supplemental cooling (sprinklers or evaporative coolers) for extreme heat.
- Relative humidity:
  75% maximum in winter; no established limit in summer
- Ventilation rate:
  Growing pig (34 to 68 kg)—3 to 35 L/s
  Finishing pig (68 to 100 kg)—5 to 60 L/s
  Gestating sow (150 kg)—6 to 70 L/s
  Boar/breeding sow (180 kg)—7 to 140 L/s

- Space:
  0.55 m^2 per pig 34 to 68 kg each
  0.75 m^2 per pig 68 to 100 kg each
  1.3 to 2.2 m^2 per pig 110 to 130 kg each

Poultry

In broiler and brooder houses, growing chicks require changing environmental conditions, and heat and moisture dissipation rates increase as the chicks grow older. Supplemental heat, usually from brooders, is used until the sensible heat produced by the birds is adequate to maintain an acceptable air temperature. At early stages of growth, moisture dissipation per bird is low. Consequently, low ventilation rates are recommended to prevent excessive heat loss. Litter is allowed to accumulate over 3 to 5 flock placements. Lack of low-cost litter material may justify the use of concrete floors. After each flock, caked litter is removed and fresh litter is added.

Housing for poultry may be open, curtain-sided or totally enclosed. Mechanical ventilation depends on the type of housing used. For open-sided housing, ventilation is generally natural airflow in warm weather, supplemented with stirring fans, and by fans with closed curtains in cold weather or during the brooding period. Mechanical ventilation is used in totally enclosed housing. Newer houses have smaller curtains and well-insulated construction to accommodate both natural and mechanical ventilation operation.

Recommendations for **broiler houses**:

- Room temperature: 15 to 27°C
- Temperature under brooder hover: 30 to 33°C, reducing 3 K per week until room temperature is reached
- Relative humidity: 50 to 80%
- Ventilation rate: Sufficient to maintain house within 1 to 2 K of outside air conditions during summer. Generally, rates are about 0.1 L/s per kilogram live mass during winter and 1 to 2 L/s per kilogram for summer conditions.
- Space: 0.06 to 0.1 m^2 per bird (for the first 21 days of brooding, only 50% of floor space is used)
- Light: Minimum of 10 lx to 28 days of age; 1 to 20 lx for growout (in enclosed housing).

Recommendations for **breeder houses** with birds on litter and slatted floors:

- Temperature: 10 to 30°C maximum; consider evaporative cooling if higher temperatures are expected.
- Relative humidity: 50 to 75%
- Ventilation rate: Same as for broilers on live mass basis.
- Space: 0.2 to 0.3 m^2 per bird

Recommendations for **laying houses** with birds in cages:

- Temperature, relative humidity, and ventilation rate: Same as for breeders.
- Space: 0.032 to 0.042 m^2 per hen minimum
- Light: Controlled day length using light-controlled housing is generally practiced (January through June).

Laboratory Animals

The well-being and experimental response of laboratory animals depends greatly on the design of the facilities. Cage type, noise levels, light levels, air quality, and thermal environment can affect animal well-being and, in many cases, affect how the animal responds to experimental treatments (Moreland 1975, Lindsey et al. 1978, Clough 1982, McPherson 1975). If any of these factors vary across treatments or even within treatments, it can affect the validity of experimental results, or at least increase experimental error. Consequently, laboratory animal facilities must be designed and maintained to expose the animals to appropriate levels of these environmental conditions and to ensure that all animals in an experiment are in a uniform environment. See Chapter 14 for additional information on laboratory animal facilities.

In the United States, recommended environmental conditions within laboratory animal facilities are usually dictated by the *Guide for the Care and Use of Laboratory Animals* (ILAR 1996). Temperature recommendations vary from 16 to 29°C depending on the species being housed. The acceptable range for relative humidity is 30 to 70%. For animals in confined spaces, daily temperature fluctuations should be kept to a minimum. Relative humidity must also be controlled, but not as precisely as temperature.

Ventilation recommendations are based on room air changes; however, cage ventilation rates may be inadequate in some cages and excessive in other cages depending on cage and facility design. ILAR (1996) recommendations for room ventilation rates of 10 to 15 air changes per hour are an attempt to provide adequate ventilation for the room and the cages. This recommendation is based on the assumption that adequate ventilation in the macroenvironment (room) provides sufficient ventilation to the microenvironment (cage). This may be a reasonable assumption when cages have a top of wire rods or mesh. However, several studies have shown that covering cages with filter tops provides a protective barrier for rodents and reduces airborne infections and diseases, especially neonatal diarrhea; but the filter can create significant differences in microenvironmental conditions.

Maghirang et al. (1995) and Riskowski et al. (1996) surveyed room and cage environmental conditions in several laboratory animal facilities and found that the animal's environmental needs may not be met even though the facilities were designed and operated according to ILAR (1996). The microenvironments were often considerably poorer than the room conditions, especially in microisolator cages. For example, ammonia levels in cages were up to 45 mg/m^3 even though no ammonia was detected in a room. Cage temperatures were up to 4 K higher than room temperature and relative humidities up to 41% higher.

Furthermore, cage microenvironments within the same room were found to have significant variation (Riskowski et al. 1996). Within the same room, cage ammonia levels varied from 0 to 45 mg/m^3; cage air temperature varied from 0.5 to 4 K higher than room temperature; cage relative humidity varied from 1 to 30% higher than room humidity, and average light levels varied from 2 to 337 lx. This survey found three identical rooms that had room ventilation rates from 4.4 to 12.5 air changes per hour (ACH) but had no differences in room or cage environmental parameters.

A survey of laboratory animal environmental conditions in seven laboratory rat rooms was conducted by Zhang et al. (1992). They found that room air ammonia levels were under 0.37 mg/m^3 for all rooms, even though room airflow varied from 11 to 24 ACH. Air exchange rates in the cages varied from less than 0.05 L/s to 1.2 L/s per rat, and ammonia levels ranged from negligible to 45 mg/m^3. Ris-kowski et al. (1996) measured several environmental parameters in rat shoebox cages in full-scale room mockups with various room and ventilation configurations. Significant variations in cage temperature and ventilation rates within a room were also found. Varying room ventilation rate from 5 to 15 ACH did not have large effects on the cage environmental conditions. These studies verify that designs based only on room air changes do not guarantee desired conditions in the animal cages.

In order to analyze the ventilation performance of different laboratory animal research facilities, Memarzadeh (1998) used **computational fluid dynamics** (CFD) to undertake computer simulation of over 100 different room configurations. CFD is a three-dimensional mathematical technique used to compute the motion of air, water, or any other gas or liquid. However, all conditions must be correctly specified in the simulation to produce accurate results. Empirical work defined inputs for such parameters as heat dissipation and surface temperature as well as the moisture, CO_2, and NH_3 mass generation rates for mice.

This approach compared favorably with experimentally measured temperatures and gas concentrations in a typical animal research facility. To investigate the relationships between room configuration parameters and the room and cage environments in laboratory animal research facilities, the following parameters were varied:

- Supply air diffuser type and orientation, air temperature, and air moisture content
- Room ventilation rate
- Exhaust location and number
- Room pressurization
- Rack layout and cage density
- Change station location, design, and status
- Leakage between the cage lower and upper moldings
- Room width

Room pressurization, change station design, and room width had little effect on ventilation performance. However, other factors found to affect either the macroenvironment or microenvironment or both led to the following observations:

- Ammonia production depends on relative humidity. Ten days after the last change of bedding, a high-humidity environment produced ammonia at about three times the rate of cages in a low-humidity environment.
- Acceptable room and cage ammonia concentrations after 5 days without changing cage bedding are produced by room supply airflow rates of around 4 L/s per kilogram of body mass of mice. This is equivalent to 5 ACH for the room with single-density racks considered in this study, and 10 ACH for the room with double-density racks. The temperature of the supply air must be set appropriately for the heat load in the room. The room with single-density racks contained 1050 mice with a total mass of 21 kg and the room with double-density racks contained 2100 mice with a total mass of 42 kg.
- Increasing the room ventilation rate has a continuous beneficial effect on the room breathing zone ventilation (as measured by CO_2 and NH_3 concentrations). For single-density racks parallel to the walls, increasing the airflow from 5 to 20 ACH reduces the breathing zone CO_2 concentration from 250 to 113 mg/m^3, a decrease of 55%. For double-density racks perpendicular to the walls, the reduction is even more dramatic—from over 540 to 167 mg/m^3 (over 70% reduction) when the airflow is increased from 5 to 20 ACH.
- Increasing the room ventilation rate does not have a large effect on the cage ventilation. Increasing the supply airflow from 5 to 20 ACH around single-density racks parallel to the walls reduces the CO_2 concentration from 3175 to 3000 mg/m^3, a reduction of only 6%. For the double-density racks perpendicular to the walls, the reduction is larger, but still only from about 4140 to 3240 mg/m^3 (around 20%)
- Both the cage and the room ammonia concentrations can be reduced by increasing the supply air temperatures. This reduces the relative humidity for a given constant moisture content in the air and the lower relative humidity leads to lower ammonia generation. Raising the supply discharge temperature from 19 to 22°C at 15 ACH raises the room temperature by 3 K to around 23°C and the cages by 2 K to around 25°C. This can reduce ammonia concentrations by up to 50%.
- Using 22°C as the supply discharge temperature at 5 ACH (the lowest flow rate considered) for double-density racks produces a room temperature around 26°C with cage temperatures only slightly higher. Although this higher temperature provides a more comfortable environment for the mice (Gordon et al. 1997), the high room temperature may be unacceptable to the scientists working in the room.
- Ceiling or high-level exhausts tend to produce lower room temperatures (for a given supply air temperature, all CFD models were designed to have 22°C at the room exhaust) when compared to low-level exhausts. This indicates that low-level exhausts are less efficient at cooling the room.
- Low-level exhausts appear to ventilate the cages slightly better (up to 27% for the radial diffuser; much less for the slot diffuser) than ceiling or high-level exhausts when the cages are placed parallel to the walls, near the exhausts. Ammonia concentration in the cages decreased even further, although this is due to the higher temperatures in the low-level exhaust cases when compared to the ceiling and high-level exhausts. The room concentrations of CO_2 and ammonia do not show that any type of supply or exhaust is significantly better or worse than the other type.

DESIGN FOR PLANT FACILITIES

Greenhouses, plant growth chambers, and other facilities for indoor crop production overcome adverse outdoor environments and provide conditions conducive to economical crop production. The basic requirements of indoor crop production are (1) adequate light; (2) favorable temperatures; (3) favorable air or gas content; (4) protection from insects and disease; and (5) suitable growing media, substrate, and moisture. Because of their lower cost per unit of usable space, greenhouses are preferred over plant growth chambers for protected crop production.

This section covers greenhouses and plant growth facilities, and Chapter 10 of the 2001 *ASHRAE Handbook—Fundamentals* describes the environmental requirements in these facilities. Figure 7 shows the structural shapes of typical commercial greenhouses. Other greenhouses may have Gothic arches, curved glazing, or simple lean-to shapes. Glazing, in addition to traditional glass, now includes both film and rigid plastics. High light transmission by the glazing is usually important; good location and orientation of the house are important in providing desired light conditions. Location also affects heating and labor costs, exposure to plant disease and air pollution, and material handling requirements. As a general rule in the northern hemisphere, a greenhouse should be placed at a distance of at least 2.5 times the height of the object closest to it in the eastern, western, and southern directions.

GREENHOUSES

Site Selection

Sunlight. Sunlight provides energy for plant growth and is often the limiting growth factor in greenhouses of the central and northern areas of North America during the winter. When planning greenhouses that are to be operated year-round, a designer should design for the greatest sunlight exposure during the short days of midwinter. The building site should have an open southern exposure, and if the land slopes, it should slope to the south.

Soil and Drainage. When plants are to be grown in the soil covered by the greenhouse, a growing site with deep, well-drained, fertile soil, preferably sandy loam or silt loam, should be chosen. Even though organic soil amendments can be added to poor soil, fewer problems occur with good natural soil. However, when good

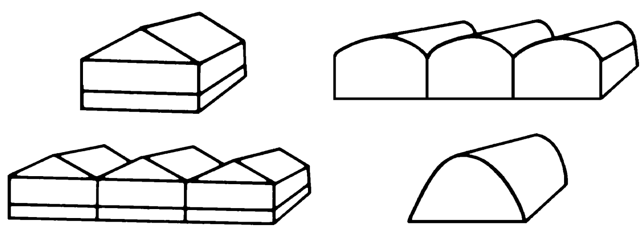

Fig. 7 Structural Shapes of Commercial Greenhouses

soil is not available, growing in artificial media should be considered. The greenhouse should be level, but the site can and often should be sloped and well-drained to reduce salt buildup and insufficient soil aeration. A high water table or a hardpan may produce water-saturated soil, increase greenhouse humidity, promote diseases, and prevent effective use of the greenhouse. If present, these problems can be alleviated by tile drains under and around the greenhouse. Ground beds should be level to prevent water from concentrating in low areas. Slopes within greenhouses also increase temperature and humidity stratification and create additional environmental problems.

Sheltered Areas. Provided they do not shade the greenhouse, surrounding trees act as wind barriers and help prevent winter heat loss. Deciduous trees are less effective than coniferous trees in midwinter, when the heat loss potential is greatest. In areas where snowdrifts occur, windbreaks and snowbreaks should be 30 m or more from the greenhouse to prevent damage.

Orientation. Generally, in the northern hemisphere, for single-span greenhouses located north of 35° latitude, maximum transmission during winter is attained by an east-west orientation. South of 35° latitude, orientation is not important, provided headhouse structures do not shade the greenhouse. North-south orientation provides more light on an annual basis.

Gutter-connected or ridge-and-furrow greenhouses are oriented preferably with the ridge line north-south regardless of latitude. This orientation permits the shadow pattern caused by the gutter superstructure to move from the west to the east side of the gutter during the day. With an east-west orientation, the shadow pattern would remain north of the gutter, and the shadow would be widest and create the most shade during winter when light levels are already low. Also, the north-south orientation allows rows of tall crops, such as roses and staked tomatoes, to align with the long dimension of the house—an alignment that is generally more suitable to long rows and the plant support methods preferred by many growers.

The slope of the greenhouse roof is a critical part of greenhouse design. If the slope is too flat, a greater percentage of sunlight is reflected from the roof surface (Figure 8). A slope with a 1:2 rise-to-run ratio is the usual inclination for a gable roof.

HEATING

Structural Heat Loss

Estimates for heating and cooling a greenhouse consider conduction, infiltration, and ventilation energy exchange. In addition, the calculations must consider solar energy load and electrical input, such as light sources, which are usually much greater for greenhouses than for conventional buildings. Generally, conduction q_c plus infiltration q_i are used to determine the peak requirements q_t for heating.

$$q_t = q_c + q_i \tag{4}$$

$$q_c = UA(t_i - t_o) \tag{5}$$

$$q_i = 0.5\ VN(t_i - t_o) \tag{6}$$

where

U = overall heat loss coefficient, W/(m^2·K) (Table 2 and Table 3)
A = exposed surface area, m^2
t_i = inside temperature, °C
t_o = outside temperature, °C
V = greenhouse internal volume, m^3
N = number of air exchanges per hour (Table 4)

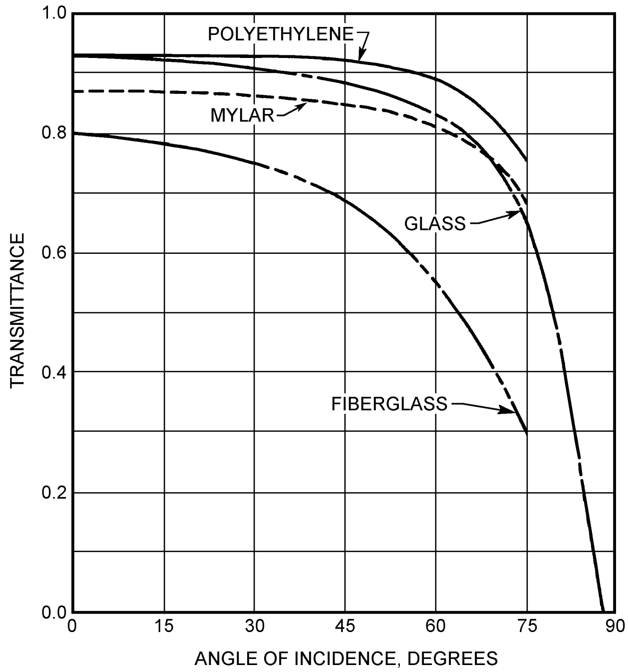

Fig. 8 Transmittance of Solar Radiation Through Glazing Materials for Various Angles of Incidence

Table 2 Suggested Heat Transmission Coefficients

		U, W/(m^2·K)
Glass		
	Single-glazing	6.4
	Double-glazing	4.0
	Insulating	Manufacturers' data
Plastic film		
	Single film[a]	6.8
	Double film, inflated	4.0
	Single film over glass	4.8
	Double film over glass	3.4
Corrugated glass fiber		
	Reinforced panels	6.8
Plastic structured sheet[b]		
	16 mm thick	3.3
	8 mm thick	3.7
	6 mm thick	4.1

[a]Infrared barrier polyethylene films reduce heat loss; however, use this coefficient when designing heating systems because the structure could occasionally be covered with non-IR materials.
[b]Plastic structured sheets are double-walled, rigid plastic panels.

Table 3 Construction U-Factor Multipliers

Metal frame and glazing system, 400 to 600 mm spacing	1.08
Metal frame and glazing system, 1200 mm spacing	1.05
Fiberglass on metal frame	1.03
Film plastic on metal frame	1.02
Film or fiberglass on wood	1.00

Table 4 Suggested Design Air Changes (N)

New Construction	
Single glass lapped (unsealed)	1.25
Single glass lapped (laps sealed)	1.0
Plastic film covered	0.6 to 1.0
Structured sheet	1.0
Film plastic over glass	0.9
Old Construction	
Good maintenance	1.5
Poor maintenance	2 to 4

Type of Framing

The type of framing should be considered in determining overall heat loss. Aluminum framing and glazing systems may have the metal exposed to the exterior to a greater or lesser degree, and the heat transmission of this metal is higher than that of the glazing material. To allow for such a condition, the U-factor of the glazing material should be multiplied by the factors shown in Table 3.

Infiltration

Equation (6) may be used to calculate heat loss by infiltration. Table 4 suggests values for air changes *N*.

Radiation Energy Exchange

Solar gain can be estimated using the procedures outlined in Chapter 29 of the 2001 *ASHRAE Handbook—Fundamentals*. As a guide, when a greenhouse is filled with a mature crop of plants, one-half the incoming solar energy is converted to latent heat; and one-quarter to one-third, to sensible heat. The rest is either reflected out of the greenhouse or absorbed by the plants and used in photosynthesis.

Radiation from a greenhouse to a cold sky is more complex. Glass admits a large portion of solar radiation but does not transmit long-wave thermal radiation in excess of approximately 5000 nm. Plastic films transmit more of the thermal radiation but, in general, the total heat gains and losses are similar to those of glass. Newer plastic films containing infrared (IR) inhibitors reduce the thermal radiation loss. Plastic films and glass with improved radiation reflection are available at a somewhat higher cost. Normally, radiation energy exchange is not considered in calculating the design heat load.

Heating

Greenhouses may have a variety of heaters. One is a convection heater that circulates hot water or steam through plain or finned pipe. The pipe is most commonly placed along walls and occasionally beneath plant benches to create desirable convection currents. A typical temperature distribution pattern created by perimeter heating is shown in Figure 9. More uniform temperatures can be achieved when about one-third the total heat comes from pipes spaced uniformly across the house. These pipes can be placed above or below the crop, but temperature stratification and shading are avoided when they are placed below. Outdoor weather conditions affect temperature distribution, especially on windy days in loosely constructed greenhouses. Manual or automatic overhead pipes are also used for supplemental heating to prevent snow buildup on the roof. In a gutter-connected greenhouse in a cold climate, a heat pipe should be placed under each gutter to prevent snow accumulation.

An overhead tube heater consists of a unit heater that discharges into 300 to 750 mm diameter plastic film tubing perforated to provide uniform air distribution. The tube is suspended at 2 to 3 m intervals and extends the length of the greenhouse. Variations include a tube and fan receiving the discharge of several unit heaters. The fan and tube system is used without heat to recirculate the air and, during cold weather, to introduce ventilation air. However, tubes sized for heat distribution may not be large enough for effective ventilation during warm weather.

Perforated tubing, 150 to 250 mm in diameter, placed at ground level heaters (underbench) can also improve heat distribution. Ideally, the ground-level tubing should draw air from the top of the greenhouse for recirculation or heating. Tubes on or near the floor have the disadvantage of being obstacles to workers and reducing usable floor space.

Underfloor heating can supply up to 25% or more of the peak heating requirements in cold climates. A typical underfloor system uses 100 mm plastic pipe spaced 300 to 400 mm on center, and covered with 20 mm of gravel or porous concrete. Hot water, not exceeding 40°C, circulates at a rate of 0.5 to 1.0 L/s per loop. Pipe loops should generally not exceed 130 m in length. This can provide 50 to 65 W/m^2 from a bare floor, and about 75% as much when potted plants or seedling flats cover most of the floor.

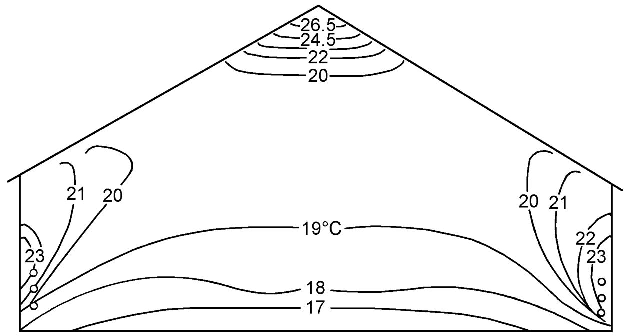

Fig. 9 Temperature Profiles in a Greenhouse Heated with Radiation Piping along the Sidewalls

Similar systems can heat soil directly, but root temperature must not exceed 25°C. When used with water from solar collectors or other heat sources, the underfloor area can store heat. This storage consists of a vinyl swimming pool liner placed on top of insulation and a moisture barrier at a depth of 200 to 300 mm below grade, and filled with 50% void gravel. Hot water from solar collectors or other clean sources enters and is pumped out on demand. Some heat sources, such as cooling water from power plants, cannot be used directly but require closed-loop heat transfer to avoid fouling the storage and the power plant cooling water.

Greenhouses can also be bottom heated with 6 mm diameter EPDM tubing (or variations of that method) in a closed loop. The tubes can be placed directly in the growing medium of ground beds or under plant containers on raised benches. The best temperature uniformity is obtained by flow in alternate tubes in opposite directions. This method can supply all the greenhouse heat needed in mild climates.

Bottom heat, underfloor heating, and under-bench heating are, because of the location of the heat source, more effective than overhead or peripheral heating, and can reduce energy loss by 20 to 30%.

Unless properly located and aimed, overhead unit heaters, whether hydronic or direct fired, do not give uniform temperature at the plant level and throughout the greenhouse. Horizontal blow heaters positioned so that they establish a horizontal airflow around the outside of the greenhouse offer the best distribution. The airflow pattern can be supplemented with the use of horizontal blow fans or circulators.

When direct combustion heaters are used in the greenhouse, combustion gases must be adequately vented to the outside to minimize danger to plants and humans from products of combustion. One manufacturer recommends that combustion air must have access to the space through a minimum of two permanent openings in the enclosure, one near the bottom. A minimum of 2200 mm^2 of free area per kilowatt input rating of the unit, with a minimum of 0.65 m^2 for each opening, whichever is greater, is recommended. Unvented direct combustion units should not be used inside the greenhouse.

In many greenhouses, a combination of overhead and perimeter heating is used. Regardless of the type of heating, it is common practice to calculate the overall heat loss first, and then to calculate the individual elements such as the roof, sidewalls, and gables. It is then simple to allocate the overhead portion to the roof loss and the perimeter portions to the sides and gables, respectively.

The annual heat loss can be approximated by calculating the design heat loss and then, in combination with the annual degree-day tables using the 18.3°C base, estimating an annual heat loss and computing fuel usage on the basis of the rating of the particular fuel used. If a 10°C base is used, it can be prorated.

Heat curtains for energy conservation are becoming more important in greenhouse construction. Although this energy savings may be considered in the annual energy use, it should not be used when calculating design heat load; the practice is to open the heat curtains during snowstorms to facilitate the melting of snow, thereby nullifying its contribution to the design heat loss value.

Air-to-air and water-to-air heat pumps have been used experimentally on small-scale installations. Their usefulness is especially sensitive to the availability of a low-cost heat source.

Radiant (Infrared) Heating

Radiant heating is used in some limited applications for greenhouse heating. Steel pipes spaced at intervals and heated to a relatively high temperature by special gas heaters serve as the source of radiation. Because the energy is transmitted by radiation from a source of limited size, proper spacing is important to completely cover the heated area. Further, heavy foliage crops can shade the lower parts of the plants and the soil, thus restricting the radiation from warming the root zone, which is important to plant growth.

Cogenerated Sources of Heat

Greenhouses have been built near or adjacent to power plants to use the heat and electricity generated by the facility. While this energy may cost very little, an adequate standby energy source must be provided, unless the power supplier can assure that it will supply a reliable, continuous source of energy.

COOLING

Solar radiation is a considerable source of sensible heat gain; even though some of this energy is reflected from the greenhouse, some of it is converted into latent heat as the plants transpire moisture, and some is converted to plant material by photosynthesis. Natural ventilation, mechanical ventilation, shading, and evaporative cooling are common methods used to remove this heat. Mechanical refrigeration is seldom used to air condition greenhouses because the cooling load and resulting cost is so high.

Natural Ventilation

Most older greenhouses and many new ones rely on natural ventilation with continuous roof sashes on each side of the ridge and continuous sashes in the sidewalls. The roof sashes are hinged at the ridge, and the wall sashes are hinged at the top of the sash. During much of the year, vents admit enough ventilating air for cooling without the added cost of running fans.

The principles of natural ventilation are explained in Chapter 26 of the 2001 *ASHRAE Handbook—Fundamentals*. Ventilation air is driven by wind and thermal buoyancy forces. Proper vent openings take advantage of pressure differences created by wind. Thermal buoyancy caused by the temperature difference between the inside and the outside of the greenhouse is enhanced by the area of the vent opening and the stack height (vertical distance between the center of the lower and upper opening). Within the limits of typical construction, the larger the vents, the greater the ventilating air exchanged. For a single greenhouse, the combined area of the sidewall vents should equal that of the roof vents. In ranges of several gutter-connected greenhouses, the sidewall area cannot equal the roof vent area.

Mechanical (Forced) Ventilation

Exhaust fans provide positive ventilation without depending on wind or thermal buoyancy forces. The fans are installed in the side or end walls of the greenhouse and draw air through vents on the opposite side or end walls. The air velocity through the inlets should not exceed 2 m/s.

Air exchange rates between 0.75 and 1 change per minute effectively control the temperature rise in a greenhouse. As shown in Figure 10, the temperature inside the greenhouse rises rapidly at lower airflow rates. At higher airflow rates the reduction of the temperature rise is small, fan power requirements are increased, and plants may be damaged by the high air speed.

Shading

Shading compounds can be applied in varying amounts to the exterior of the roof of the greenhouse to achieve up to 50% shading. Durability of these compounds varies—ideally the compound will wear away during the summer and leave the glazing clean in the fall when shading is no longer needed. In practice, some physical cleaning is needed. Compounds used formerly usually contained lime, which corrodes aluminum and attacks some caulking. Most compounds used currently are formulated to avoid this problem.

Mechanically operated shade cloth systems with a wide range of shade levels are also available. They are mounted inside the greenhouse to protect them from the weather. Not all shading compounds or shade cloths are compatible with all plastic glazings, so the manufacturers' instructions and precautions should be followed.

Evaporative Cooling

Fan-and-Pad Systems. Fans for fan-and-pad evaporative cooling are installed in the same manner as fans used for mechanical ventilation. Pads of cellulose material in a honeycomb form are installed on the inlet side. The pads are kept wet continuously when evaporative cooling is needed. As air is drawn through the pads, the water evaporates and cools the air. New pads cool the air by about 80% of the difference between the outdoor dry-bulb and wet-bulb temperature, or to 1.5 to 2 K above the wet-bulb temperature.

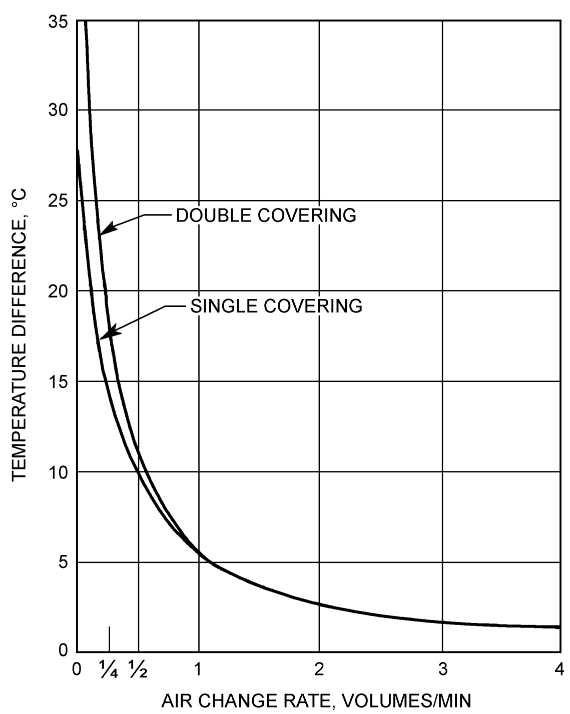

Fig. 10 Influence of Air Exchange Rate on Temperature Rise in Single- and Double-Covered Greenhouses

The empirical base rate of airflow is 40 L/s per square metre of floor area. This flow rate is modified by multiplying it by factors for elevation (F_e), maximum interior light intensity (F_l), and the allowable temperature rise between the pad and the fans (F_t). These factors are listed in Table 5. The overall factor for the house is given by the following equation:

$$F_h = F_e F_l F_t \tag{7}$$

The maximum fan-to-pad distance should be kept to 53 m, although some greenhouses with distances of 68 m have shown no serious reduction in effectiveness. With short distances, the air velocity becomes so low that the air feels clammy and stuffy, even though the airflow is sufficient for cooling. Therefore, a velocity factor F_v listed in Table 6 is used for distances less than 30 m. For distance less than 30 m, F_v is compared to F_h. The factor that gives the greatest airflow is used to modify the empirical base rate. For fan-to-pad distances greater than 30 m, F_v can be ignored.

Table 5 Multipliers for Calculating Airflow for Fan-and-Pad Cooling

Elevation (Above Sea Level)		Max. Interior Light Intensity		Fan-to-Pad Temp. Difference	
m	F_e	klx	F_l	K	F_t
<300	1.00	40	0.74	5.5	0.71
300	1.03	45	0.84	5.0	0.78
600	1.08	50	0.93	4.5	0.87
900	1.12	55	1.02	4.0	0.98
1200	1.16	60	1.12	3.5	1.12
1500	1.20	65	1.21	3.0	1.31
1800	1.25	70	1.30	2.5	1.58
2100	1.29	75	1.39		
2400	1.33	80	1.49		
2700	1.37	85	1.58		

Table 6 Velocity Factors for Calculating Airflow for Fan-to-Pad Cooling

Fan-to-Pad Distance, m	F_v	Fan-to-Pad Distance, m	F_v
6	2.26	20	1.23
8	1.96	22	1.17
10	1.75	24	1.13
12	1.60	26	1.08
14	1.48	28	1.04
16	1.38	30	1.00
18	1.30		

Table 7 Recommended Air Velocity Through Various Pad Materials

Pad Type and Thickness	Air Face Velocity Through Pad,[a] m/s
Corrugated cellulose, 100 mm thick	1.25
Corrugated cellulose, 150 mm thick	1.75

[a]Speed may be increased by 25% where construction is limiting.

Table 8 Recommended Water Flow and Sump Capacity for Vertically Mounted Cooling Pad Materials

Pad Type and Thickness	Minimum Water Rate per Linear Metre of Pad, L/s	Minimum Sump Capacity per Unit Pad Area, L/m^2
Corrugated cellulose, 100 mm thick	0.10	30
Corrugated cellulose, 150 mm thick	0.16	40

For best performance, pads should be installed on the windward side, and fans spaced within 7.5 m of each other. Fans should not blow toward pads of an adjacent house unless it is at least 15 m away. Fans in adjacent houses should be offset if they blow toward each other and are within 4.5 m of each other.

Recommended air velocities through commonly used pads are listed in Table 7. Water flow and sump capacities are shown in Table 8. The system should also include a small, continuous bleed-off of water to reduce the buildup of dirt and other impurities.

Unit Evaporative Coolers. This equipment contains the pads, water pump, sump, and fan in one unit. Unit coolers are primarily used for small compartments. They are mounted 4.5 to 6 m apart on the sidewall and blow directly into the greenhouse. They cool a distance of up to 15 m from the unit. A side sash on the outside opposite wall is the best outlet, but roof vents may also work. The roof vent on the same side as the unit should be slightly open for better air distribution. If the roof vent on the opposite side is opened instead, air may flow directly out the vent and not cool the opposite side of the greenhouse.

Fog. In a direct-pressure atomizer, a high-pressure pump forces water at 5.5 to 7 MPa through a special fog nozzle. Fog is considered to be a water droplet smaller than 40 µm in diameter. The direct-pressure atomizer generates droplets of 35 µm or less. This requires a superior filter to minimize clogging of the very small nozzle orifices.

A line of nozzles placed along the top of the vent opening can cool the entering air nearly to its wet-bulb temperature. Additional lines in the greenhouse continue to cool the air as it absorbs heat in the space.

Fogging will cool satisfactorily with less airflow than fan-and-pad systems, but the fan capacity must still be based on one air change per minute to ventilate the greenhouse when the cooler will be used without fog.

OTHER ENVIRONMENTAL CONTROLS

Humidity Control

At various times during the year, humidity may need to be controlled in the greenhouse. When the humidity is too high at night, it can be reduced by adding heat and ventilating simultaneously. When the humidity is too low during the day, it can be increased by turning on a fog or mist nozzle.

Winter Ventilation

During the winter, houses are normally closed tightly to conserve heat, but photosynthesis by the plants may lower the carbon dioxide level to such a point that it slows plant growth. Some ventilation helps maintain inside carbon dioxide levels. A normal rate of airflow for winter ventilation is 10 to 15 L/s per square metre of floor area.

Air Circulation

Continuous air circulation within the greenhouse reduces still-air conditions that favor plant diseases. Recirculating fans, heaters that blow air horizontally, and fans attached to polyethylene tubes are used to circulate air. The amount of recirculation has not been well defined, except that some studies have shown high air velocities (greater than 1.0 m/s) can harm plants or reduce growth.

Insect Screening

Insect screening is being used to cover vent inlets and outlets. These fine-mesh screens increase the resistance to airflow, which must be considered when selecting ventilation fans. The screen manufacturer should provide static pressure data for its screens. The pressure drop through the screen can be reduced by framing out from the vent opening to increase the area of the screen.

Table 9 Constants to Convert to W/m²

Light Source	klx	μmol/s²·m²
400 to 700 nm		
Incandescent (INC)	3.99	0.20
Fluorescent cool white (FCW)	2.93	0.22
Fluorescent warm white (FWW)	2.81	0.21
Discharge clear mercury (HG)	2.62	0.22
Metal halide (MH)	3.05	0.22
High-pressure sodium (HPS)	2.45	0.20
Low-pressure sodium (LPS)	1.92	0.20
Daylight	4.02	0.22

Note: 1 μmol/(s·m²) = 1 einstein/(s·m²)

Carbon Dioxide Enrichment

Carbon dioxide is added in some greenhouse operations to increase growth and enhance yields. However, CO_2 enrichment is practical only when little or no ventilation is required for temperature control. Carbon dioxide can be generated from solid CO_2 (dry ice), bottled CO_2, and misting carbonated water. Bulk or bottled CO_2 gas is usually distributed through perforated tubing placed near the plant canopy. Carbon dioxide from dry ice is distributed by passing greenhouse air through an enclosure containing dry ice. Air movement around the plant leaf increases the efficiency with which the plant absorbs whatever CO_2 is available. One study found an air speed of 0.5 m/s to be equivalent to a 50% enrichment in CO_2 without forced air movement.

Radiant Energy

Light is normally the limiting factor in greenhouse crop production during the winter. North of the 35th parallel, light levels are especially inadequate or marginal in fall, winter, and early spring. Artificial light sources, usually high-intensity discharge (HID) lamps, may be added to greenhouses to supplement low natural light levels. High-pressure sodium (HPS), metal halide (MH), low-pressure sodium (LPS), and occasionally, mercury lamps coated with a color-improving phosphor, are currently used. Since differing irradiance or illuminance ratios are emitted by the various lamp types, the incident radiation is best described as radiant flux density (W/m²) between 400 and 850 nm, or as photon flux density between 400 and 700 nm, rather than in photometric terms of lux.

To assist in relating irradiance to more familiar illuminance values, Table 9 shows constants for converting illuminance (lux) and photon flux density [μmol/(s·m²)] of HPS, MH, LPS, and other lamps to the irradiance (W/m²).

Table 10 gives values of suggested irradiance at the top of the plant canopy, duration, and time of day for supplementing natural light levels for specific plants.

HID lamps in luminaires developed specifically for greenhouse use are often placed in a horizontal position, which may decrease both the light output and the life of the lamp. These drawbacks may be balanced by improved horizontal and vertical uniformity as compared to industrial parabolic reflectors.

Photoperiod Control

Artificial light sources are also used to lengthen the photoperiod during the short days of winter. Photoperiod control requires much lower light levels than those needed for photosynthesis and growth. Photoperiod illuminance needs to be only 6 to 12 W/m². The incandescent lamp is the most effective light source for this purpose due to its higher far-red component. Lamps such as 150 W (PS-30) silverneck lamps spaced 3 to 4 m on centers and 4 m above the plants provide a cost-effective system. Where a 4 m height is not practical, 60 W extended service lamps on 2 m centers are satisfactory. One method of photoperiod control is to inter-

Table 10 Suggested Radiant Energy, Duration, and Time of Day for Supplemental Lighting in Greenhouses

Plant and Stage of Growth	W/m²	Duration: Hours	Duration: Time
African violets	12 to 24	12 to 16	0600-1800
early-flowering			0600-2200
Ageratum early-flowering	12 to 48	24	
Begonias—fibrous rooted branching and early-flowering	12 to 24	24	
Carnation branching and early-flowering	12 to 24	16	0800-2400
Chrysanthemums	12 to 24	16	0800-2400
vegetable growth branching and multiflowering	12 to 24	8	0800-1600
Cineraria seedling growth (four weeks)	6 to 12	24	
Cucumber rapid growth and early-flowering	12 to 24	24	
Eggplant early-fruiting	12 to 48	24	
Foliage plants (Philodendron, Schefflera) rapid growth	6 to 12	24	
Geranium branching and early-flowering	12 to 48	24	
Gloxinia	12 to 48	16	0800-2400
early-flowering	6 to 12	24	
Lettuce rapid growth	12 to 48	24	
Marigold early-flowering	12 to 48	24	
Impatiens—New Guinea branching and early-flowering	12	16	0800-2400
Impatiens—Sultana branching and early-flowering	12 to 24	24	
Juniper vegetative growth	12 to 48	24	
Pepper early-fruiting, compact growth	12 to 24	24	
Petunia branching and early-flowering	12 to 48	24	
Poinsettia—vegetative growth	12	24	
branching and multiflowering	12 to 24	8	0800-1600
Rhododendron vegetative growth (shearing tips)	12	16	0800-2400
Roses (hybrid teas, miniatures) early-flowering and rapid regrowth	12 to 48	24	
Salvia early-flowering	12 to 48	24	
Snapdragon early-flowering	12 to 48	24	
Streptocarpus early-flowering	12	16	0800-2400
Tomato rapid growth and early-flowering	12 to 24	16	0800-2400
Trees (deciduous) vegetative growth	6	16	1600-0800
Zinnia early-flowering	12 to 48	24	

rupt the dark period by turning the lamps on at 2200 and off at 0200. The 4 h interruption, initially based on chrysanthemum response, induces a satisfactory long-day response in all photoperiodically sensitive species. Many species, however, respond to interruptions of 1 h or less. Demand charges can be reduced in large installations by operating some sections from 2000 to 2400 and others from 2400 to 0400. The biological response to these schedules, however, is much weaker than with the 2200 to 0200 schedule, so some varieties may flower prematurely. If the 4 h interruption period is used, it is not necessary to keep the light on throughout the interruption period. Photoperiod control of most plants can be accomplished by operating the lamps on light and dark cycles with 20% "on" times; for example, 12 s/min. The length of the dark period in the cycle is critical, and the system may fail if the dark period exceeds about 30 min. Demand charges can be reduced by alternate scheduling of the "on" times between houses or benches without reducing the biological effectiveness of the interruption.

Plant displays in places such as showrooms or shopping malls require enough light for plant maintenance and a spectral distribution that best shows the plants. Metal halide lamps, with or without incandescent highlighting, are often used for this purpose. Fluorescent lamps, frequently of the special phosphor plant-growth type, enhance color rendition, but are more difficult to install in aesthetically pleasing designs.

Design Conditions

Plant requirements vary from season to season and during different stages of growth. Even different varieties of the same species of plant may vary in their requirements. State and local cooperative extension offices are a good source of specific information on design conditions affecting plants. These offices also provide current, area-specific information on greenhouse operations.

Alternate Energy Sources and Energy Conservation

Limited progress has been achieved in heating commercial greenhouses with solar energy. Collecting and storing the heat requires a volume at least one-half the volume of the entire greenhouse. Passive solar units work at certain times of the year and, in a few localities, year-round.

If available, reject heat is a possible source of winter heat. Winter energy and solar (photovoltaic) sources are possible future energy sources for greenhouses, but the development of such systems is still in the research stage.

Energy Conservation. A number of energy-saving measures (e.g., thermal curtains, double glazing, and perimeter insulation) have been retrofitted to existing greenhouses and incorporated into new construction. Sound maintenance is necessary to keep heating system efficiency at a maximum level.

Automatic controls, such as thermostats, should be calibrated and cleaned at regular intervals, and heating-ventilation controls should interlock to avoid simultaneous operation. Boilers that can burn more than one type of fuel permit use of the most inexpensive fuel available.

Modifications to Reduce Heat Loss

Film covers that reduce heat loss are used widely in commercial greenhouses, particularly for growing foliage plants and other species that grow under low light levels. Irradiance (intensity) is reduced 10 to 15% per layer of plastic film.

One or two layers of transparent 0.10 or 0.15 mm continuous-sheet plastic is stretched over the entire greenhouse (leaving some vents uncovered), or from the ridge to the sidewall ventilation opening. When two layers are used, (outdoor) air at a pressure of 50 to 60 Pa is introduced continuously between the layers of film to maintain the air space between them. When a single layer is used, an air space can be established by stretching the plastic over the glazing bars and fastening it around the edges, or a length of polyethylene tubing can be placed between the glass and the plastic and inflated (using outside air) to stretch the plastic sheet.

Double-Glazing Rigid Plastic. Double-wall panels are manufactured from acrylic and polycarbonate plastics, with walls separated by about 10 mm. Panels are usually 1.2 m wide and 2.4 m or longer. Nearly all types of plastic panels have a high thermal expansion coefficient and require about 1% expansion space (10 mm/m). When a panel is new, light reduction is roughly 10 to 20%. Moisture accumulation between the walls of the panels must be avoided.

Double-Glazing Glass. The framing of most older greenhouses must be modified or replaced to accept double glazing with glass.

Light reduction is 10% more than with single glazing. Moisture and dust accumulation between glazings increases light loss. As with all types of double glazing, snow on the roof melts slowly and increases light loss. Snow may even accumulate sufficiently to cause structural damage, especially in gutter-connected greenhouses.

Silicone Sealants. Transparent silicone sealant in the glass overlaps of conventional greenhouses reduces infiltration and may produce heat savings of 5 to 10% in older structures. There is little change in light transmission.

Precautions. The various methods described above reduce heat loss by reducing conduction and infiltration. They may also cause more condensation, higher relative humidity, lower carbon dioxide concentration, and an increase in ethylene and other pollutants. Combined with the reduced light levels, these factors may cause delayed crop production, elongated plants, soft plants, and various deformities and diseases, all of which reduce the marketable crop.

Thermal blankets are any flexible material that is pulled from gutter to gutter and end to end in a greenhouse, or around and over each bench, at night. Materials ranging from plastic film to heavy cloth, or laminated combinations, have successfully reduced heat losses by 25 to 35% overall. Tightness of fit around edges and other obstructions is more important than the kind of material used. Some films are vaportight and retain moisture and gases. Others are porous and permit some gas exchange between the plants and the air outside the blanket. Opaque materials can control crop day length when short days are part of the requirement for that crop. Condensation may drip onto and collect on the upper sides of some blanket materials to such an extent that they collapse.

Multiple-layer blankets, with two or more layers separated by air spaces, have been developed. One such design combines a porous-material blanket and a transparent film blanket; the latter is used for summer shading. Another design has four layers of porous, aluminum foil-covered cloths, with the layers separated by air.

Thermal blankets may be opened and closed manually as well as automatically. The decision to open or close should be based on the irradiance level and whether it is snowing, rather than on the time of day. Two difficulties with thermal blankets are the physical problems of installation and use in greenhouses with interior supporting columns, and the loss of space due to shading by the blanket when it is not in use during the day.

Other Recommendations. While the foundation can be insulated, the insulating materials must be protected from moisture, and the foundation wall should be protected from freezing. All or most of the north wall can be insulated with opaque or reflective-surface materials. The insulation reduces the amount of diffuse light entering the greenhouse and, in cloudy climates, causes reduced crop growth near the north wall.

Ventilation fan cabinets should be insulated, and fans not needed in winter should be sealed against air leaks. Efficient management and operation of existing facilities are the most cost-effective ways to reduce energy use.

PLANT GROWTH ENVIRONMENTAL FACILITIES

Controlled-environment rooms (CERs), also called plant growth chambers, include all controlled or partially controlled environmental facilities for growing plants, except greenhouses. CERs are indoor facilities. Units with floor areas less than 5 m^2 may be moveable with self-contained or attached refrigeration units. CERs usually have artificial light sources, provide control of temperature and, in some cases, control relative humidity and CO_2 level.

CERs are used to study all aspects of botany. Some growers use growing rooms to increase seedling growth rate, produce more uniform seedlings, and grow specialized, high-value crops. The main components of the CER are (1) an insulated room or an insulated box with an access door; (2) a heating and cooling mechanism with associated air-moving devices and controls; and (3) a lamp module at the top of the insulated box or room. CERs are similar to walk-in cold storage rooms, except for the lighting and larger refrigeration system needed to handle heat produced by the lighting.

Location

The location for a CER must have space for the outside dimensions of the chamber, refrigeration equipment, ballast rack, and control panels. Additional space around the unit is necessary for servicing the various components of the system and, in some cases, for substrate, pots, nutrient solutions, and other paraphernalia associated with plant research. The location also requires electricity (on the order of 300 W/m^2 of controlled environment space), water, and compressed air.

Construction and Materials

Wall insulation should have a thermal conductance of less than 0.15 W/($m^2 \cdot$K). Materials should resist corrosion and moisture. The interior wall covering should be metal, with a high-reflectance white paint, or specular aluminum with a reflectivity of at least 80%. Reflective films or similar materials can be used, but will require periodic replacement.

Floors and Drains

Floors that are part of the CER should be corrosion-resistant. Tar or asphalt waterproofing materials and volatile caulking compounds should not be used because they will likely release phytotoxic gases into the chamber atmosphere. The floor must have a drain to remove spilled water and nutrient solutions. The drains should be trapped and equipped with screens to catch plant and substrate debris.

Plant Benches

Three bench styles for supporting the pots and other plant containers are normally encountered in plant growth chambers: (1) stationary benches; (2) benches or shelves built in sections that are adjustable in height; and (3) plant trucks, carts, or dollies on casters, which are used to move plants between chambers, greenhouses, and darkrooms. The bench supports containers filled with moist sand, soil, or other substrate, and is usually rated for loads of at least 240 kg/m^2. The bench or truck top should be constructed of nonferrous, perforated metal or metal mesh to allow free passage of air around the plants and to let excess water drain from the containers to the floor and subsequently to the floor drain.

Normally, benches, shelves, or truck tops are adjustable in height so that small plants can be placed close to the lamps and thus receive a greater amount of light. As the plants grow, the shelf or bench is lowered so that the tops of the plants continue to receive the original radiant flux density.

Control

Environmental chambers require complex controls to provide the following:

- Automatic transfer from heating to cooling with 1 K or less dead zone and adjustable time delay.
- Automatic daily switching of the temperature set point for different day and night temperatures (setback may be as much as 5 K).
- Protection of sensors from radiation. Ideally, the sensors are located in a shielded, aspirated housing, but satisfactory performance can be attained by placing them in the return air duct.
- Control of the daily duration of light and dark periods. Ideally, this control should be programmable to change the light period each day to simulate the natural progression of day length. Photoperiod control, however, is normally accomplished with mechanical time clocks, which must have a control interval of 5 min or less for satisfactory timing.
- Protective control to prevent the chamber temperature from going more than a few degrees above or below the set point. Control should also prevent short cycling of the refrigeration system, especially when the condensers are remotely located.
- Audible and visual alarms to alert personnel of malfunctions.
- Maintenance of relative humidity to prescribed limits.

Data loggers, recorders, or recording controllers are recommended for monitoring daily operation. Solid-state, microprocessor-based control is not yet widely used. However, programming flexibility and control performance should improve as microprocessor control is developed for CER use.

Heating, Air Conditioning, and Airflow

When the lights are on, cooling will normally be required, and the heater will rarely be called on to operate. When the lights are off, however, both heating and cooling may be needed. Conventional refrigeration is generally used with some modification. Direct expansion units usually operate with a hot-gas bypass to prevent numerous on-off cycles, and secondary coolant may use aqueous ethylene glycol rather than chilled water. Heat is usually provided by electric heaters, but other energy sources can be used, including hot gas from the refrigeration.

The plant compartment is the heart of the growth chamber. The primary design objective, therefore, is to provide the most uniform, consistent, and regulated environmental conditions possible. Thus, airflow must be adequate to meet specified psychrometric conditions, but it is limited by the effects of high air speed on plant growth. As a rule, the average air speed in CERs is restricted to about 0.5 m/s.

To meet the uniform conditions required by a CER, conditioned air is normally moved through the space from bottom to top, although an increasing number of CERs use top-to-bottom airflow. There is no apparent difference in plant growth between horizontal, upward, or downward airflow when the speed is less than 0.9 m/s. Regardless of the method, a temperature gradient is certain to exist, and the design should keep the gradient as small as possible. Uniform airflow is more important than the direction of flow; thus, selection of properly designed diffusers or plenums with perforations is essential for achieving it.

The ducts or false sidewalls that direct air from the evaporator to the growing area should be small, but not so small that the noise increases appreciably more than acceptable building air duct noise. CER design should include some provision for cleaning the interior of the air ducts.

Air-conditioning equipment for relatively standard chambers provides temperatures that range from 7 to 35°C. Specialized CERs that require temperatures as low as –20°C need low-temperature refrigeration equipment and devices to defrost the evaporator without increasing the growing area temperature. Other chambers that

Table 11 Input Power Conversion of Light Sources

Lamp Identification		Total Input Power, W	Radiation (400-700 nm), %	Radiation (400-850 nm), %	Other Radiation, %	Conduction and Convection, %	Ballast Loss, %
Incandescent	INC, 100A	100	7	15	75	10	0
Fluorescent							
Cool white	FCW	46	21	21	32	34	13
Cool white	FCW	225	19	19	34	35	12
Warm white	FWW	46	20	20	32	35	13
Plant growth A	PGA	46	13	13	35	39	13
Plant growth B	PGB	46	15	16	34	37	13
Infrared	FIR	46	2	9	39	39	13
Discharge							
Clear mercury	HG	440	12	13	61	17	9
Mercury deluxe	HG/DX	440	13	14	59	18	9
Metal halide	MH	460	27	30	42	15	13
High-pressure sodium	HPS	470	26	36	36	13	15
Low-pressure sodium	LPS	230	27	31	25	22	22

Note: Conversion efficiency is for lamps without luminaires. Values compiled from manufacturers' data, published information, and unpublished test data by R.W. Thimijan.

require temperatures as high as 45°C need high-temperature components. The air temperature in the growing area must be controlled with the least possible variation about the set point. Temperature variation about the set point can be held to 0.3 K using solid-state controls, but in most existing facilities, the variation is 0.5 to 1 K.

The relative humidity in many CERs is simply an indicator of the existing psychrometric conditions and is usually between 50 and 80%, depending on the temperature. Relative humidity in the chamber can be increased by steam injection, misting, hot-water evaporators, and other conventional humidification methods. Steam injection causes the least temperature disturbance, and sprays or misting cause the greatest disturbance. Complete control of relative humidity requires dehumidification as well as humidification.

A typical humidity control includes a cold evaporator or steam injection to adjust the chamber air dew point. The air is then conditioned to the desired dry-bulb temperature by electric heaters, a hot-gas bypass evaporator, or a temperature-controlled evaporator. A dew point lower than about 5°C cannot be obtained with a cold plate dehumidifier because of icing. Dew points lower than 5°C usually require a chemical dehumidifier in addition to the cold evaporator.

Lighting Environmental Chambers

The type of light source and the number of lamps used in CERs are determined by the desired plant response. Traditionally, cool-white fluorescent plus incandescent lamps that produce 10% of the fluorescent illuminance are used. Nearly all illumination data are based on either cool-white or warm-white fluorescent, plus incandescent lamps. A number of fluorescent lamps have special phosphors hypothesized to be the spectral requirements of the plant. Some of these lamps are used in CERs, but there is little data to suggest that they are superior to cool-white and warm-white lamps. In recent years, high-intensity discharge lamps have been installed in CERs, either to obtain very high radiant flux densities, or to reduce the electrical load while maintaining a light level equal to that produced by the less efficient fluorescent-incandescent systems.

One method to design lighting for biological environments is to base light source output recommendations on photon flux density $\mu mol/(s \cdot m^2)$ between 400 and 700 nm, or, less frequently, as radiant flux density between 400 and 700 nm, or 400 and 850 nm. Rather than basing illuminance measurements on human vision, this enables comparisons between light sources as a function of plant photosynthetic potential. Table 9 shows constants for converting various measurement units to W/m^2. However, instruments that measure the 400 to 850 nm spectral range are generally not available, and some controversy exists about the effectiveness of 400 to 850 nm as compared to the 400 to 700 nm range in photosynthesis. The power conversion of various light sources is listed in Table 11.

Table 12 Approximate Mounting Height and Spacing of Luminaires in Greenhouses

Lamp and Wattage	Irradiation, W/m^2 6	12	24	48
	Height and Spacing, m			
HPS (400 W)	3.0	2.3	1.6	1.0
LPS (180 W)	2.4	1.7	1.2	0.8
MH (400 W)	2.7	2.0	1.4	0.9

The design requirements for plant growth lighting differ greatly from those for vision lighting. Plant growth lighting requires a greater degree of horizontal uniformity and, usually, higher light levels than vision lighting. In addition, plant growth lighting should have as much vertical uniformity as possible—a factor rarely important in vision lighting. Horizontal and vertical uniformity are much easier to attain with linear or broad sources, such as fluorescent lamps, than with point sources, such as HID lamps. Tables 12 and 13 show the type and number of lamps, mounting height, and spacing required to obtain several levels of incident energy. Since the data were taken directly under lamps with no reflecting wall surfaces nearby, the incident energy is perhaps one-half of what the plants would receive if the lamps had been placed in a small chamber with highly reflective walls.

Extended-life incandescents or traffic signal lamps, which have a much longer life, will lower lamp replacement requirements. These lamps have lower lumen output, but are nearly equivalent in the red portion of the spectrum. For safety, porcelain lamp holders and heat-resistant lamp wiring should be used. Lamps used for CER lighting include fluorescent lamps (usually 1500 mA), 250, 400, and occasionally 1000 W HPS and MH lamps, 180 W LPS lamps, and various sizes of incandescent lamps. In many installations, the abnormally short life of incandescent lamps is due to vibration from the lamp loft ventilation or from cooling fans. Increased incandescent lamp life under these conditions can be attained by using lamps constructed with a C9 filament.

Energy-saving lamps have approximately equal or slightly lower irradiance per input watt. Since the irradiance per lamp is lower, there is no advantage to using these lamps, except in tasks that can be accomplished with low light levels. Light output of all lamps declines with use, except perhaps for low-pressure sodium (LPS) lamps, which appear to maintain approximately constant output but require an increase in input power during use.

Table 13 Height and Spacing of Luminaires

Light Source	Radiant Flux Density, W/m²						
	0.3	**0.9**	**3**	**9**	**18**	**24**	**50**
Fluorescent—Cool White							
40 W single 1.2 m lamp, 3.2 klm							
Radiant power, W/m², 400 to 700 nm	0.3	0.9	2.9	8.8			
Illumination, klx	0.10	0.30	1.0	3.0			
Lamps per 10 m²	1.1	3.3	11	33			
Distance from plants, m	2.9	1.7	0.92	0.53			
40 W 2-lamp fixtures (1.2 m), 6.4 klm							
Radiant power, W/m², 400 to 700 nm	0.3	0.9	2.9	8.8			
Illumination, klx	0.10	0.30	1.0	3.0			
Fixtures per 10 m²	0.6	1.7	5.5	16.7			
Distance from plants, m	4.1	2.4	1.3	0.75			
215 W, 2-2.4 m lamps, 31.4 klm							
Radiant power, W/m², 400 to 700 nm	0.3	0.9	2.9	8.8	17.6	23.5	49.0
Illumination, klx	0.10	0.30	1.0	3.0	6.0	8.0	16.7
Lamps per 10 m²	0.1+	0.4	1.2	3.6	7.1	9.3	20
Distance from plants, m	8.8	5.1	2.8	1.6	1.1	1.0	0.7
High-Intensity Discharge							
Mercury-1 400 W parabolic reflector							
Radiant power, W/m², 400 to 700 nm	0.28	0.84	2.80	8.39	16.8	22.4	46.6
Illumination, klx	0.1	0.32	1.1	3.2	6.4	8.6	18.0
Lamps per 10 m²	0.2	0.5	1.6	4.8	9.3	13.0	27
Distance from plants, m	7.6	4.4	2.4	1.4	1.0	0.8	0.6
Metal halide-1 400 W							
Radiant power, W/m², 400 to 700 nm	0.77	0.80	2.68	8.03	16.1	21.4	44.6
Illumination, klx	0.09	0.26	0.88	2.6	5.3	7.0	15.0
Lamps per 10 m²	0.09	0.2	0.7	2.2	4.4	5.8	12.0
Distance from plants, m	11.3	6.5	3.6	2.1	1.5	1.3	0.87
High-pressure sodium 400 W							
Radiant power, W/m², 400 to 700 nm	0.22	0.65	2.18	6.52	13.0	17.4	36.2
Illumination, klx	0.09	0.27	0.89	2.7	5.3	7.1	15.0
Lamps per 10 m²	0.05	0.14	0.5	1.4	2.8	3.6	7.6
Distance from plants, m	14.2	8.2	4.5	2.6	1.8	1.6	1.1
Low-pressure sodium 180 W							
Radiant power, W/m², 400 to 700 nm	0.26	0.79	2.64	7.93	15.9	21.1	44.0
Illumination, klx	0.14	0.41	1.4	4.1	8.3	11.0	23.0
Lamps per 10 m²	0.08	0.24	0.8	2.4	4.9	6.5	13.6
Distance from plants, m	10.7	6.2	3.4	2.0	1.4	1.2	0.83
Incandescent							
Incandescent 100 W							
Radiant power, W/m², 400 to 700 nm	0.14	0.41	1.38	4.14	8.28	11.0	23.0
Illumination, klx	0.033	0.10	0.33	1.0	2.0	2.7	5.6
Lamps per 10 m²	0.5	1.6	5.2	15.8	32	42	87
Distance from plants, m	4.2	4.2	1.3	0.77	0.54	0.47	0.33
Incandescent 150 W flood							
Radiant power, W/m², 400 to 700 nm	0.14	0.41	1.38	4.14	8.28	11.0	23.0
Illumination, klx	0.033	0.098	0.33	1.0	2.0	2.6	5.5
Lamps per 10 m²	0.3	0.9	3.3	9.3	19.5	26	54
Distance from plants, m	5.4	3.1	1.7	1.0	0.7	0.6	0.4
Incandescent-Hg 160 W							
Radiant power, W/m², 400 to 700 nm	0.14	0.41	1.38	4.14	8.28	11.0	23.0
Illumination, klx	0.050	0.15	0.50	1.5	3.0	4.0	8.3
Lamps per 10 m²	0.7	2.0	6.9	20.4	42	56	111
Distance from plants, m	3.7	2.1	1.2	0.67	0.47	0.41	0.28
Sunlight							
Radiant power, W/10 m²	0.22	0.66	2.21	6.65	13.3	17.7	76.9
Illumination, klx	0.054	0.16	0.54	1.6	3.2	4.3	8.9

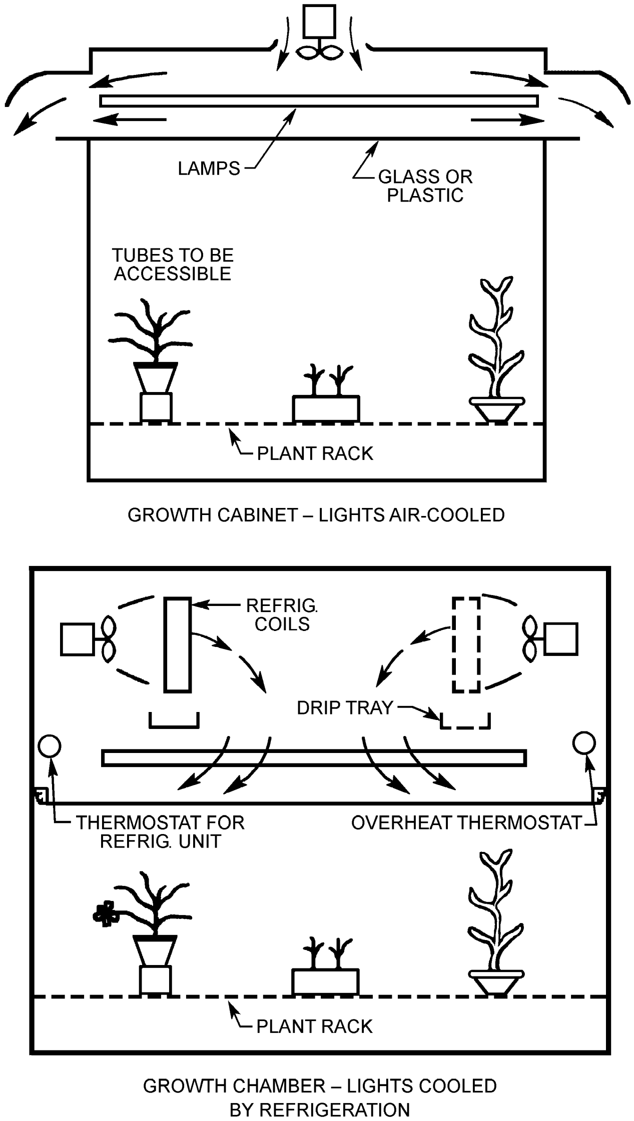

Fig. 11 Cooling Lamps in Growth Chambers

Fluorescent and metal halide designs should be based on 80% of the initial light level. Most CER lighting systems have difficulty maintaining a relatively constant light level over considerable periods of time. Combinations of MH and HPS lamps compound the problem, because the lumen depreciation of the two light sources is significantly different. Thus, over time, the spectral energy distribution at plant level will shift toward the HPS. Lumen output can be maintained in two ways: (1) individual lamps, or a combination of lamps, can be switched off initially and activated as the lumen output decreases; and (2) the oldest 25 to 33% of the lamps can be replaced periodically. Solid-state dimmer systems are commercially available only for low-wattage fluorescent lamps and for mercury lamps.

Large rooms, especially those constructed as an integral part of the building and retrofitted as CERs, rarely separate the lamps from the growing area with a transparent barrier. Rooms designed as CERs (at the time a building is constructed) and freestanding rooms or chambers usually separate the lamp from the growing area with a barrier of glass or rigid plastic. Light output from fluorescent lamps is a function of the temperature of the lamp. Thus, the barrier serves a two-fold purpose: (1) to maintain optimum lamp temperature when the growing area temperature is higher or lower than optimum, and (2) to reduce the thermal radiation entering the growing area. Fluorescent lamps should operate in an ambient temperature and airflow environment that will maintain the tube wall temperature at 40°C. Under most conditions, the light output of HID lamps is not affected by ambient temperature. The heat must be removed, however, to prevent high thermal radiation from causing adverse biological effects (see Figure 11).

Transparent glass barriers remove nearly all radiation from about 350 to 2500 nm. Rigid plastic is less effective than glass; however, the lower mass and lower breakage risk of plastic makes it a popular barrier material. Ultraviolet is also screened by both glass and plastic (more by plastic). Special UV-transmitting plastic (which degrades rapidly) can be obtained if the biological process requires UV light. When irradiance is very high, especially from HID lamps or large numbers of incandescent lamps or both, rigid plastic can soften from the heat and fall from the supports. Furthermore, very high irradiance and the resulting high temperatures can cause plastic to darken, which can increase the absorptivity and temperature enough to destroy it. Under these conditions, heat-resistant glass may be necessary. The lamp compartment and barrier absolutely require positive ventilation regardless of the light source, and the lamp loft should have limit switches that will shut down the lamps if the temperature rises to a critical level.

Table 14 Mounting Height for Luminaires in Storage Areas

	Survival = 3 W/m²		Maintenance = 9 W/m²	
	Distance, m	lux	Distance, m	lux
Fluorescent (F)				
FCW two 40 W	0.9	1000	0.75	3000
FWW	0.9	1000	0.75	3000
FCW two 215 W	2.8	1000	1.6	3000
Discharge (HID)				
MH 400 W	3.3	800	2.0	2400
HPS 400 W	4.5	800	2.5	2400
LPS 180 W	3.4	1300	1.2	4000
Incandescent (INC)				
INC 160 W	1.3	350	0.3	1000
INC-HG 160 W	1.2	500	1.6	1500
DL	—	500	—	1500

OTHER PLANT ENVIRONMENTAL FACILITIES

Plants may be held or processed in warehouse-type structures prior to sale or use in interior landscaping. Required temperatures range from slightly above freezing for cold storage of root stock and cut flowers, to 20 to 25°C for maintaining growing plants, usually in pots or containers. Provision must be made for venting fresh air to avoid CO_2 depletion.

Light duration must be controlled by a time clock. When they are in use, lamps and ballasts produce almost all the heat required in an insulated building. Ventilation and cooling may be required. Illumination levels depend on plant requirements. Table 14 shows approximate mounting heights for two levels of illumination. Luminaires mounted on chains permit lamp height to be adjusted to compensate for varying plant height.

The main concerns for interior landscape lighting are how it renders the color of plants, people, and furnishings, as well as how it meets the minimum irradiation requirements of plants. The temperature required for human occupancy is normally acceptable for plants. Light level and duration determine the types of plants that can be grown or maintained. Plants grow when exposed to higher levels, but do not survive below the suggested minimum.

Plants may be grouped into three levels based on the following of irradiances:

Low (survival): A minimum light level of 0.75 W/m^2 and a preferred level of 3 W/m^2 irradiance for 8 to 12 h daily.

Medium (maintenance): A minimum of 3 W/m^2 and a preferred level of 9 W/m^2 irradiance for 8 to 12 h daily.

High (propagation): A minimum of 9 W/m^2 and a preferred level of 24 W/m^2 irradiance for 8 to 12 h daily.

Fluorescent (warm-white), metal halide, or incandescent lighting is usually chosen for public places. Table 13 lists the irradiance of various light sources.

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