

CHAPTER 25. ENVIRONMENTAL CONTROL FOR ANIMALS AND PLANTS

THE design of plant and animal environmental housing is complicated because many environmental factors affect the production and well-being of living organisms. Designers should consider that equipment must repay costs through improved economic productivity. Engineers, likewise, must balance costs of modifying the environment against potential economic losses incurred through plants or animals kept in a less than ideal environment.

Thus, design of plant and animal housing is affected by financial considerations, in addition to concern for the well-being of workers and animals, and regulations on pollution, sanitation, and health assurance.

1. DESIGN FOR PLANT AND ANIMAL ENVIRONMENTS

1.1 ENVIRONMENTAL MANAGEMENT

Temperature and humidity, air movement, air quality, light, and gases (e.g., carbon dioxide, ammonia) are important environmental parameters to manage for the healthy and productivity of plants and animals. Due to the economic restrictions on these facilities, it is unusual to see commercial HVAC systems, including refrigeration-based cooling equipment, to manage these indoor environments. Maintenance of the HVAC equipment used in indoor plant and animal environments is often the responsibility of the farm owner or farm manager and often leads to more simplified designs that can be controlled automatically or manually. Many of the systems used in plant and animal environments are the same or similar and often rely on ambient controls to determine their design and operation. Both plant and animal spaces tend to have high internal latent loads that must be accounted for in the HVAC designs.

1.2 VENTILATION SYSTEMS

Natural Ventilation

The principles of natural ventilation are explained in [Chapter 16 of the 2021 ASHRAE Handbook—Fundamentals](#). Natural ventilation depends on pressure differences caused by wind and temperature differences between the inside and outside environments. Well-designed natural ventilation keeps temperatures reasonably stable, when automatic controls are used to regulate ventilation openings based on outdoor temperature and wind conditions. Some buildings include a combination of mechanical and natural ventilation, providing flexibility to the user on which system to operate based on outdoor conditions (temperature and wind), as well as the desired ventilation rates.

Usually, a design includes an open ridge (with or without a rain cover) and openable sidewalls. Within the limits of typical construction, the larger the vents, the greater the ventilating air exchanged. Without adequate vent opening area and placement, and depending on the outdoor conditions (wind and air temperature), air may not be distributed evenly throughout the structure, creating a non-uniform environment. Further, wide buildings inhibit air movement in and through the building. Small screens and square edges around sidewall openings can significantly reduce airflow through vents.

Thermal buoyancy is enhanced by the area of the vent opening and the stack height (vertical distance between the center of the lower and upper opening). For buoyancy-driven natural ventilation, ideally the roof and sidewall opening areas will be equal, with sidewall openings no less than 50% of the ridge vent openings. Wind-driven natural ventilation is enhanced when the openings are oriented toward prevailing winds.

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 inlet fans to introduce air into an occupied space and separate fans to remove air. When these fans are matched in capacity and operation, they can create a neutral-pressure system.

Positive-Pressure Ventilation. Fans blow outdoor air into the ventilated space, forcing indoor air out through any planned outlets and through unplanned leaks in the envelope (exfiltration). The energy used by fan motors and rejected as heat is added to the building (an advantage in cold weather, but a disadvantage in hot weather). Positive-pressure

ventilation systems typically provide the advantage of distributing the air to the occupied zone using duct and diffuser systems.

Negative-Pressure Ventilation. Fans located at one end of the building exhaust air from the ventilated space while drawing outdoor air in through planned inlets and unplanned leaks through the envelope (infiltration). Air distribution in negative-pressure ventilation is often less complex and costly than positive- or neutral-pressure systems. Planned ceiling and wall inlets control and distribute air in the buildings. However, at low airflow rates, negative-pressure ventilation may not distribute air uniformly because of unplanned air leaks and wind pressure effects. Supplemental air mixing may be necessary.

Neutral-Pressure Ventilation. Neutral-pressure (push/pull) ventilation typically uses 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.

Allowances should be made for reduced fan performance caused by 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.

1.3 COOLING SYSTEMS

Evaporative Cooling

Evaporative cooling works best in areas with low relative humidity, but significant benefits can be obtained even in the humid southeastern United States. Initial cost, operating expense, and maintenance problems are all relatively low compared to other types of cooling systems.

Design. The pad area should be sized to maintain air velocities between 0.3 and 1.8 m/s through the pads to reduce pressure drop. For most pad systems, these velocities produce evaporative efficiencies between 70 and 75%; they also increase pressures against the ventilating fans from 10 to 30 Pa, depending on pad design. Air velocities across the cooling pad should not exceed 2.5 m/s to prevent water carryover and excessive pressure drops that would reduce fan performance and evaporative cooling efficiencies. Whenever possible, fans should exhaust away from pads on adjacent buildings. The building and pad system must be airtight because air leaks caused by the negative-pressure ventilation reduce airflow through the pads, and hence reduce cooling effectiveness.

Regular preventive maintenance is essential. Water bleed-off and the addition of algaecides to the water are recommended. Similarly, water flow to the pads should be shut off multiple times per week with the ventilation fans operating to allow the pads to dry out, reducing algae growth on the pad. When pads are not used in cool weather, they can be sealed to prevent air infiltration through them. The most serious problem encountered with evaporative pads for agricultural applications is clogging by dust, other airborne particles, and mineral deposits from water. To prevent mineralization of the pads, water softeners and filters can be used.

High-pressure fogging with water pressure of greater than 7.0 MPa is an alternative strategy for reducing air temperature and humidifying the space. The high pressure creates a fine aerosol of water that is more easily evaporated than larger water particles, helping to prevent the wetting of plants, floors, and other surfaces. Timers, thermostats, and humidistats are used to regulate the rate and frequency of fogging. Foggers can also be used with naturally ventilated, open-sided housing. Low-pressure misting 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 dairy and 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 over high-pressure fog systems. Timers that operate long enough to just coat the animals and remain off long enough for evaporation to occur are ideal to conserve water and maximize cooling. In practice, controllers typically offer set duty cycles triggered by indoor temperature (e.g., 2 to 3 min on a 15 to 20 min cycle). Low-pressure misting systems are not recommended for plant environments due to low evaporation rates and risks for pathogen growth.

Fogging and misting systems required preventative maintenance of the nozzles, distribution lines, and pump. Water filters can be used to remove debris and minerals from the water before it is delivered to the production area. Nozzles can be cleaned with chemical cleaners and mechanically with a fine brush to remove external debris.

High-pressure fog and low-pressure mist systems are challenging to design and control. Determining the optimal distribution pattern, spray angle, and water flow rate and frequency depends on the source and direction of airflow, location and height of plants and animals, and the climate.

Mechanical Refrigeration (Air Conditioning)

Mechanical refrigeration can be designed for effective plant and animal cooling. It is typically considered uneconomical for most animal and greenhouse production facilities, and is most commonly used for **indoor plant environments (IPEs)** without sunlight.

Ventilation Heat Exchangers

Heat exchangers can reclaim some of the heat lost through the exhaust air when ventilating a building. Ventilating heat exchangers may be used to recover either sensible or total energy. In general, the amount of energy saved during the cold periods of the year exceeds the energy saved during warm summer months. However, predicting fuel savings based on savings obtained during the coldest periods overestimates 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 not properly designed, these problems result in either reduced efficiency and/or the inconvenience of frequent cleaning.

1.4 HEATING SYSTEMS

Heating Systems

Greenhouses and livestock housing may have a variety of heaters available to them. Heating systems need to perform well in a potentially dusty, humid, and corrosive environment due to ammonia production (livestock) or sulfur applications (greenhouse). 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°C base, estimating an annual heat loss and computing fuel usage on the basis of the rating of the particular fuel used. If a 50°F/10°C base is used, it can be prorated for both greenhouses and livestock housing. Heating is more common for greenhouses than for livestock housing because animals generally produce enough heat to make up for the losses through ventilation and envelope.

1.5 AIR DISTRIBUTION SYSTEMS

Air Distribution and Circulation

Air distribution is the process of delivering and mixing air within the indoor plant environment or livestock facility. The air can be introduced to the structure through positive pressure, negative pressure, or neutral pressure relationships between the inside and outside (see the section on Mechanical Ventilation).

Positive-Pressure Air Distribution. 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. Zhang (1994) describes detailed design procedures for perforated ventilation tubes. However, dust in the ducts is of concern when air is recirculated, particularly when cold incoming air condenses moisture in the tubes.

Plastic tubes and fabric or metal ducts can be used to both deliver and distribute air to the space. Tubes and ducts may be located overhead (greenhouse and livestock) or under plant-growing benches. Plastic tubes are commonly used in greenhouse and animal facilities and are typically made from polyethylene film with holes punched along the tube's length to distribute air. Plastic tubes are susceptible to dirt and pathogen growth. Fabric ducts are often permeable, with hole diameters and locations engineered to produce specified air velocities. Fabric ducts are often cleanable and may come with antibacterial properties to minimize pathogen risks. Metal ducts are most often used in fully enclosed IPEs and rely on the use of diffusers and dampers to control airflow and velocity. To minimize corrosion in the humid environment, stainless steel and aluminum are preferred.

With positive pressure systems, air is distributed to tubes and ducts using a blower fan. The fan may be used to deliver hot air from an overhead heater, cool air from an evaporatively cooled chamber, or air directly from the occupied space.

Negative-Pressure Air Distribution. Negative-pressure systems that use exhaust fans and inlets rely on pressure differences across the structure to deliver air to the space. Sizing and layout of the inlets influence how fresh air is distributed. Negative-pressure ventilation that relies on cracks around doors and windows does not distribute fresh air effectively.

A properly planned inlet system distributes fresh air equally throughout the building. The inlets on negative-pressure structures may be located at the opposite end of the exhaust fans, along the sidewalls, or through the ceiling by using the attic as a plenum. Building widths narrower than 6 m may only need inlets along one sidewall.

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. At 4 m/s, the inlet velocity is generally high enough to throw incoming air about 6 m into the building. If the inlet velocity is too low in the winter, incoming cold air may create drafts near the inlet.

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. Because the distribution of the inlet area is based on the geometry and size of the building, specific recommendations are difficult.

The use of bird screens, insect screens, light traps, wet walls, and other devices restrict airflow. Negative-pressure inlets can be actuated mechanically or adjust their opening based on static pressure. Enough static pressure is needed to throw air into the space; however, too much static pressure will reduce fan performance and limit the volume of air brought into the space.

Air Circulation and Mixing. Once the air has been delivered to the occupied space, it is often circulated and mixed to create a more uniform environment and to prevent pockets of stale or stagnant air. In the case of plants, air movement facilitates growth and helps prevent nutrient deficiencies associated with poor airflow. For animals, air movement can help prevent animals from overheating and eliminate ammonia.

Circulation fans can move air horizontally, vertically, or at an angle depending on the application and need.

Horizontal-airflow (HAF) fans are frequently used to circulate hot air produced by overhead heating systems and mix it with colder air near the ground where plants and animals reside. HAF fans also help to move air when there are limited inlets or exhaust fans are disabled. They are typically situated above the plants and animals, and may be suspended from the roof structure or attached to the trusses or walls.

Vertical airflow (VAF) fans are usually ceiling suspended and can be used to blow air directly onto plants and animals to remove temperature gradients in the structure. VAF fans can also facilitate evaporation from surfaces, such as the ground and plant leaves, by breaking up the boundary layer. These fans come in three basic types: (1) high-volume low-speed (HVLS), (2) small-diameter ceiling fans, or (3) "v-flo" circulating fans.

HAF fans may be stationary or oscillating. In livestock buildings, fans may be angled down to create airspeed for convective cooling of the animals. Circulation fans may operate continuously or be operated based on a temperature sensor.

Baffles may be used to reduce stratification and distribute air to plants and animals to reduce the boundary layer and improve evaporation and circulation. In animal structures, baffles may be located in the ceiling to create turbulence and push air down toward the animals. In IPEs, baffles may be located along the sidewalls to push air toward the center of the building.

The layout of the plant or animal space can also affect air movement. For plant environments, configuring the planting rows and spacing to channel air from inlet to outlet across all plants when exhaust fans are turned on. For animal spaces, inlets are often set just below the eave below the sidewall to facilitate airflow across the ceiling; however, feed water and gas lines that are run along the ceiling can obstruct the inlet distribution and desired air mixing patterns.

Fans

Fans used in plant and animal structures are used to supply, recirculate, exhaust, and mix air. In greenhouses and livestock barns, fans should be located such that blow in the same general direction as prevailing winds. 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 , 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. Rain hoods slanted down and away from the structure help drain water away from the structure. Supply fans that distribute air through metal, fabric, or polyducts should have a static pressure of at least 125 Pa.

Fans should be tested with all accessories (e.g., louvers, guards, hoods) in place, just as they will be installed in the building. The accessories have a major effect on fan performance. Third-party test data should be used to obtain fan performance and energy efficiencies for fan selection (BESS Lab 2022).

Flow Control. Modulating airflow to meet changing indoor and outdoor conditions can improve control of temperature and humidity inside the plant and animal environment. The minimum ventilation rate to remove moisture, reduce air contaminant concentrations, and keep water from freezing should always be provided. The maximum ventilation rate is typically based on removal of heat and temperature control during peak cooling conditions.

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) using multispeed fans [larger fans (400 W and up) with two flow rates, the lower being about 60% of the maximum rate]; and (4) using 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.

Air Velocity. The average air velocity inside a plant and animal structure depends on the building geometry, inlet and outlet velocities, distance from air inlets and outlets, and obstructions to airflow within the structure. Air velocity can be increased with air circulation fans that blow 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. Without the use of circulation fans, air velocities may be low at the plant or animal level. In general, it is good design practice to limit

the throw distance from air inlets (wall or ceiling) to less than 6 m, from perforated tubes and circulation fans to less than 10 ft3 m.

1.6 SENSORS AND CONTROLS

Sensors

Sensors may be used to monitor the environment and control the equipment used to manage the environment. Sensors are commonly used to measure temperature, humidity, carbon dioxide, light levels, static pressure, and other variables important to maintain a healthy and productive plant and animal environment. Environmental sensors should be placed where they respond to representative conditions experienced by the plants or animals to most effectively manage the environment. Sensors need protection and should be positioned to prevent potential physical or moisture damage (i.e., away from exterior walls, animals, equipment, ventilation inlets, water pipes, lights, heater exhausts, or any other objects that will unduly affect performance). Sensors also require periodic adjustment (e.g., calibration) based on accurate readings taken in the immediate proximity of the animal and plant space.

Controls

Automatic and manual control systems for environment control range in complexity, technology, and capability. Timers are often used to control lights, minimum ventilation fans, shade screens and thermal curtains, or other equipment that needs to operate at a specific time or for a specific duration. Thermostats and humidistats are commonly used to operate equipment based on real-time measurements in order to meet targeted indoor conditions. Commercial HVAC equipment often have on-board or integrated temperature and humidity sensors with programmable control algorithms.

Third-party building management systems and modern control systems can have a range of customizable configurations and expansion capabilities through a modular, card-based design to fit the unique housing styles of plants and animals. These systems may be used to control various equipment based on inputs from multiple environmental sensors, and may also include inputs about labor, energy, and production metrics to optimize equipment operation. For IPEs without sunlight, light sensors may be used to control the operating mode of HVAC equipment. Integrated and powerful software tools allow the control to be easily programmed for day-to-day and complex tasks. Other features include network access for remote management of the device, ability to monitor water, power, and gas meters, lights, feed and water pumps, generators, and people movement.

2. DESIGN FOR ANIMAL ENVIRONMENTS

Typical animal production aims to 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. Detailed information is available in a series of handbooks published by the MidWest Plan Service. These include *Mechanical Ventilating Systems for Livestock Housing* (MWPS 1990a), *Natural Ventilating Systems for Livestock Housing and Heating* (MWPS 1989), and *Cooling and Tempering Air for Livestock Housing* (MWPS 1990b). ASAE *Monograph 6, Ventilation of Agricultural Structures* (Hellickson and Walter 1983), also gives more detailed information.

2.1 DESIGN APPROACH

Environmental control systems are typically designed to maintain thermal and air quality conditions within an acceptable range and as near the ideal show as is practicable. Equipment is usually sized assuming steady-state energy and mass conservation equations. Experimental measurements show 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](#)).

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.

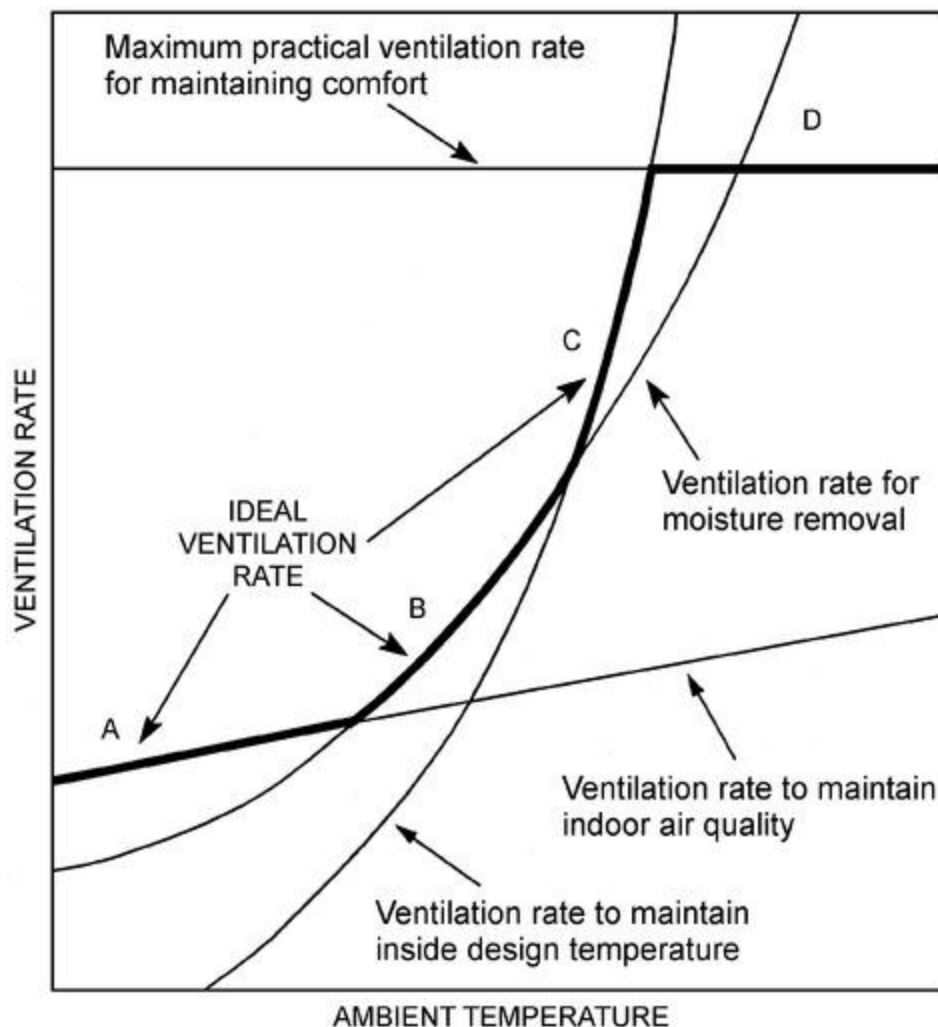


Figure 1. Logic for Selecting Appropriate Ventilation Rate in Livestock Buildings (Adapted from Christianson and Fehr 1983)

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 or above 60 air changes per hour (ACH) as a practical maximum.

Temperature Control

The temperature in 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 heat transfer through walls, ceiling or roof, and ground is calculated as presented in [Chapters 25 to 27 of the 2021 ASHRAE Handbook—Fundamentals](#).

Mature animals typically produce more heat per unit floor area than do young stock. Chapter 10 of the 2021 *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 14 of the 2021 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 2021 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. Spilled water 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.

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

During cold weather, 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 allowed during extremely 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. High moisture levels can also aggravate contaminant problems. The most common air contaminants in animal buildings are particulate matter (PM) and gases. In animal buildings, particulate matter originates mainly from feed, litter, fecal materials, and other animal substances. Particulates include solid particles (or dust), liquid droplets, and microorganisms, can be deposited deep within the respiratory system. Particulates carry allergens that cause discomfort and health problems for workers in animal housing facilities. They also carry much of the odors in animal housing facilities, for potentially 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/m³. Dust has not been a major problem in dairy buildings; one two-year study found an average of only 0.5 mg/m³ in a naturally ventilated dairy barn. Poultry building dust levels average around 2 to 7 mg/m³, but levels up to 18 to 29 mg/m³ have been measured during high activity.

The most common gas contaminants are ammonia, hydrogen sulfide, other odorous compounds, carbon dioxide, and carbon monoxide. Ammonia, which results from decomposition of manure, is the most important chronically present contaminant gas. Typical ammonia levels measured have been 7 to 37 mg/m³ in poultry units, 0 to 15 mg/m³ in cattle buildings, 4 to 22 mg/m³ in swine units with liquid manure systems, and 7 to 37 mg/m³ in swine units with solid floors (Ni et al. 1998a). Up to 150 mg/m³ have been measured in swine units in winter. Ammonia should be maintained below 18 mg/m³ and, ideally, below 7 mg/m³.

Maghirang et al. (1995) and Zhang et al. (1992) found ammonia levels in laboratory animal rooms to be negligible, but concentrations could reach 45 mg/m³ in cages. Weiss et al. (1991) found ammonia levels in rat cages of up to 260 mg/m³ with four male rats per cage and 50 mg/m³ 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/m³ nine days after cleaning the cage.

Hydrogen sulfide, a by-product of 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/m³). A typical level of hydrogen sulfide in swine buildings is around 200 to 500 µg/m³ (Ni et al. 1998b). However, levels can reach 280 to 460 mg/m³, and possibly up to 1.4 to 11 g/m³ during in-building manure agitation.

Odors from animal facilities are an increasing concern, both in the facilities and surrounding areas. Odors result from both gases and particulates; particulates are of primary concern because odorous gases can be quickly diluted below odor threshold concentrations in typical weather conditions, whereas particulates can retain odor for long periods. Methods that control particulate and odorous gas concentrations in the air also 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/m³ in nearly all instances when the external temperature was above 0°C but almost always above 5400 mg/m³ 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/m³. Air quality control based on carbon dioxide concentrations was suggested by Donham et al. (1989). They suggested a carbon dioxide concentration of 2770 mg/m³ 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/m³ 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 sources
2. Remove contaminants from the air by air cleaning (filters)
3. Reduce contaminant concentration by dilution (ventilation)

The first line of defense is to reduce release of contaminants from the source, or at least to intercept and remove them before they reach workers and animals. Animal feces and urine are the largest sources of contaminants, but feed,

litter, and animal bodies (dander) 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 enough to produce large quantities of contaminants. Using ventilation to remove air uniformly from manure storage or collection areas helps eliminate 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. Because 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 to avoid potentially fatal concentrations of gases.

Methods of removing contaminants from the air are essentially limited to particulate removal, because 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 because of the large quantity of particulates and the difficulty in drawing particulates from the room and through a filter. Air scrubbers can 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 particulate 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 prevention.

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.

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 0.75 m/s .

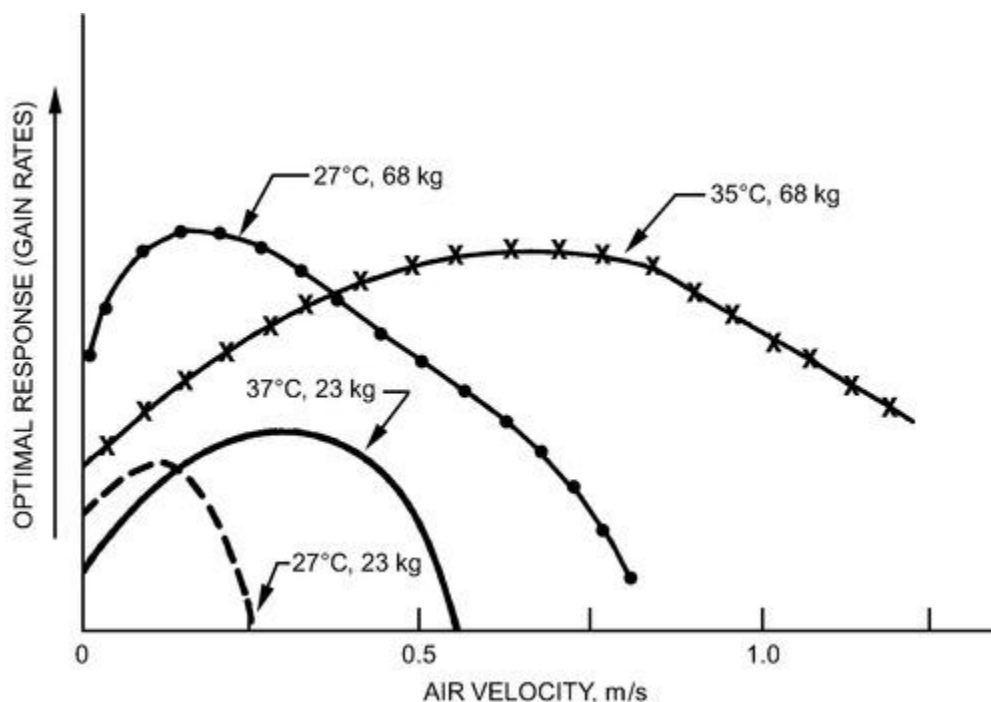


Figure 2. Response of Swine to Air Velocity

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 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 negative pressure inside the shelter, which could cause rain and snow to be drawn into the building on the leeward side. These shelters do not protect against high air temperature or high humidity but may provide protection from solar loads.

In warmer climates, shades often provide adequate shelter, especially for large, mature animals such as dairy cows. Shades are commonly used in the southwestern United States, and 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 southwestern United States, 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 shelter makes maximum use of radiant heat sinks, such as the cold sky, and gives maximum protection from direct solar radiation and irradiation due to high surface temperature around the shelter. Good design considers geometric orientation and material selection, including roof surface treatment and insulation material on the surfaces. An ideal shelter also accounts for all heat sources within the shelter, including latent and sensible heat from the animals, and uses a controller to manage ventilation to remove heat and moisture from the space.

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.

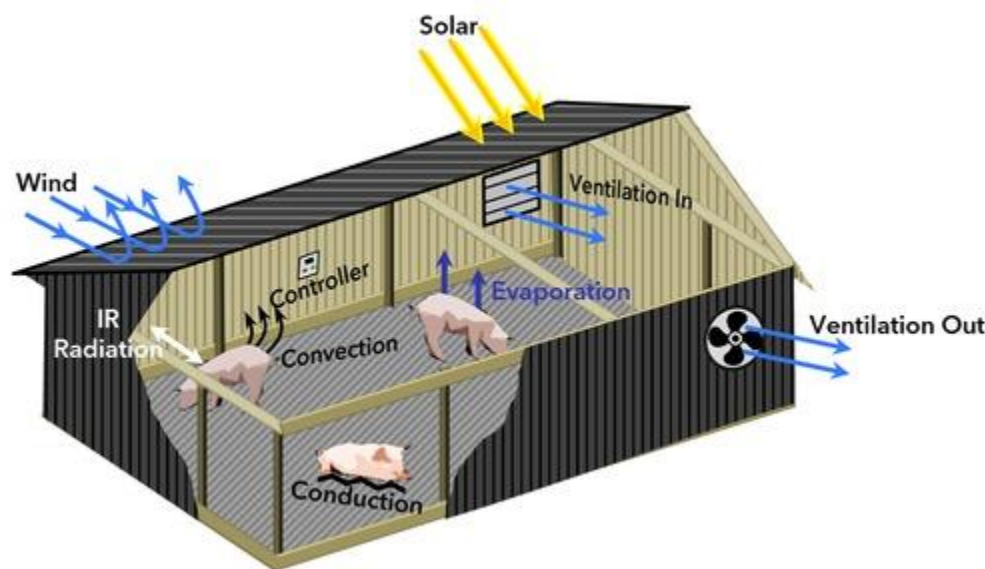


Figure 3. Energy Exchange Between Farm Animal and Surroundings in Hot Environment

2.2 COOLING AND HEATING

MWPS (1990b) details design procedures for cooling and heating. 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.

Table 1 Minimum Recommended Overall Coefficients of Heat Transmission *U* for Insulated Assemblies^{a,b}

Climatic Zone ^d	Recommended Minimum <i>U</i> , W/(m ² · K) ^c					
	Unconditioned		Minimally Conditioned		Conditioned	
	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 *Standard* C236 or C976 or calculate by the procedures presented in the 2021 *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).

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.

Unconditioned buildings have indoor conditions about the same as outdoor 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.

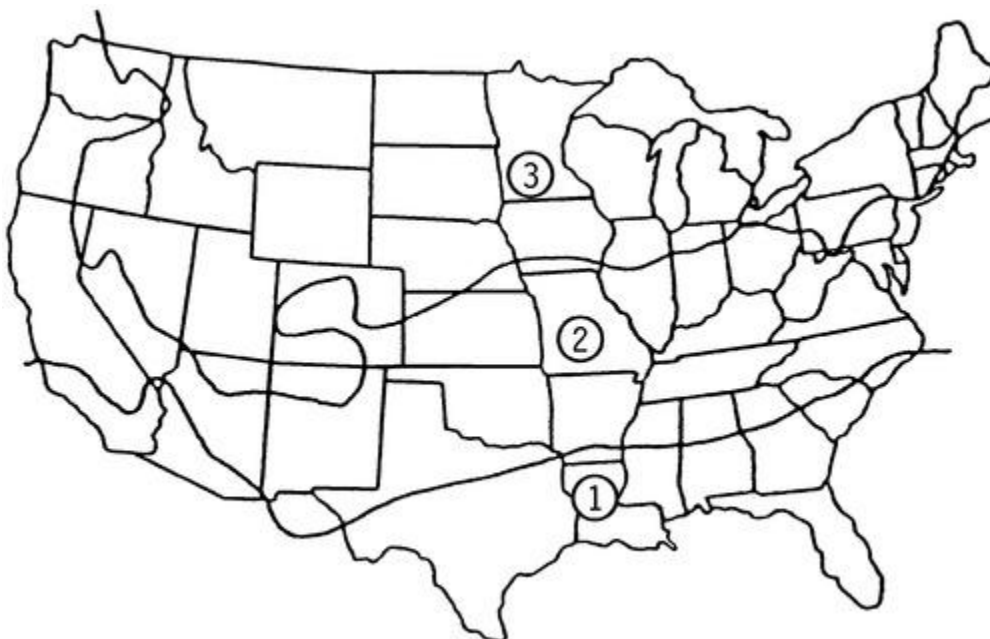


Figure 4. Climatic Zones (Reprinted with permission from ASAE Standard S401.2)

Minimally conditioned 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.

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

Cooling

Supplemental cooling of livestock buildings may be necessary during heat waves to prevent heat prostration, mortality, or serious losses in production and reproduction. Different approaches can be proposed for cooling livestock shelters as described in the section on Cooling Systems. These include the use of evaporative cooling, mechanical refrigeration, earth tubes and heat exchangers.

Evaporative Cooling

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.

High-pressure fogging with water pressure of 7.0 MPa is preferred to pad coolers for cooling 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 dairy and 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., 30 to 60 s on a 5 to 15 min cycle) help to conserve water.

Mechanical Refrigeration (Air Conditioning)

Air-conditioning loads for dairy housing may require 215 W or more per cow and for high-value swine housing (i.e., gestation, breeding, boars) may require 0.83 kW per pig. Recirculating conditioned air is usually not feasible because of high contaminant levels in the air in the animal housing; therefore, if air conditioning is used, it is typically a single-pass system. 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 pre-wean 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.

Heating

Most animals can produce enough heat to maintain target indoor temperatures if they are held at the right stocking density. Supplemental heating may be required for smaller animals or low stocking densities. The most typical heating systems used in animal facilities are natural-gas or propane-fired forced-air heaters or boilers to produce hot water for radiant heating.

Supplemental Heating. For poultry weighing 3.3 lb/1.5 kg or more, for pigs heavier than 23 kg, and for other large animals such as cattle, body heat of animals at recommended space allocations is usually sufficient to maintain moderate temperatures (i.e., above 10°C) in a well-insulated structure. Combustion-type or electric 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 moisture removal. Various types of heating equipment may be included in ventilation, but they need to perform well in dusty and corrosive atmospheres.

Heat Exchangers

Ventilation accounts for 70 to 90% of the heat losses in typical livestock facilities during winter. However, predicting fuel savings based on savings obtained during the coldest periods overestimates yearly savings from a heat exchanger. Estimates of energy savings based on air enthalpy can improve the accuracy of the predictions.

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.

Air Velocity

Increasing air velocity helps to facilitate the cooling of mature animals. It is especially beneficial when combined with skin wetting for 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 blow 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.

2.3 VENTILATION

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 outdoor air temperature and/or the amount of ventilation required.

Mechanical Ventilation

Negative-pressure ventilation systems are more commonly used than positive-pressure ventilation in animal housing. Simple openings and baffled slots in walls and ceilings help control and distribute air in the building.

When positive-pressure ventilation systems are used, if vapor barriers are not complete, moisture can condense within the envelope during cold weather, which can cause deterioration of building materials and reduce insulation effectiveness. With positive-pressure ventilation, outdoor air is frequently delivered to the attic, which has inlets to distribute air down into occupied space. Fans may also deliver air through polytubes or, less commonly, push air directly into the building.

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.

2.4 VENTILATION MANAGEMENT

Air Distribution

Inlet Design. Inlet flow characteristics were studied extensively in the early development of animal housing ventilation systems (Albright 1990). Example research results for hinged baffle and center-ceiling flat baffle slotted inlets were determined (Figure 5). Airflow rates can be calculated for the baffles in Figure 5 by the following:

For Case A:

$$Q = 1.1 W p^{0.5} \tag{1}$$

For Case B:

$$Q = 0.71 W p^{0.5} \tag{2}$$

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

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

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

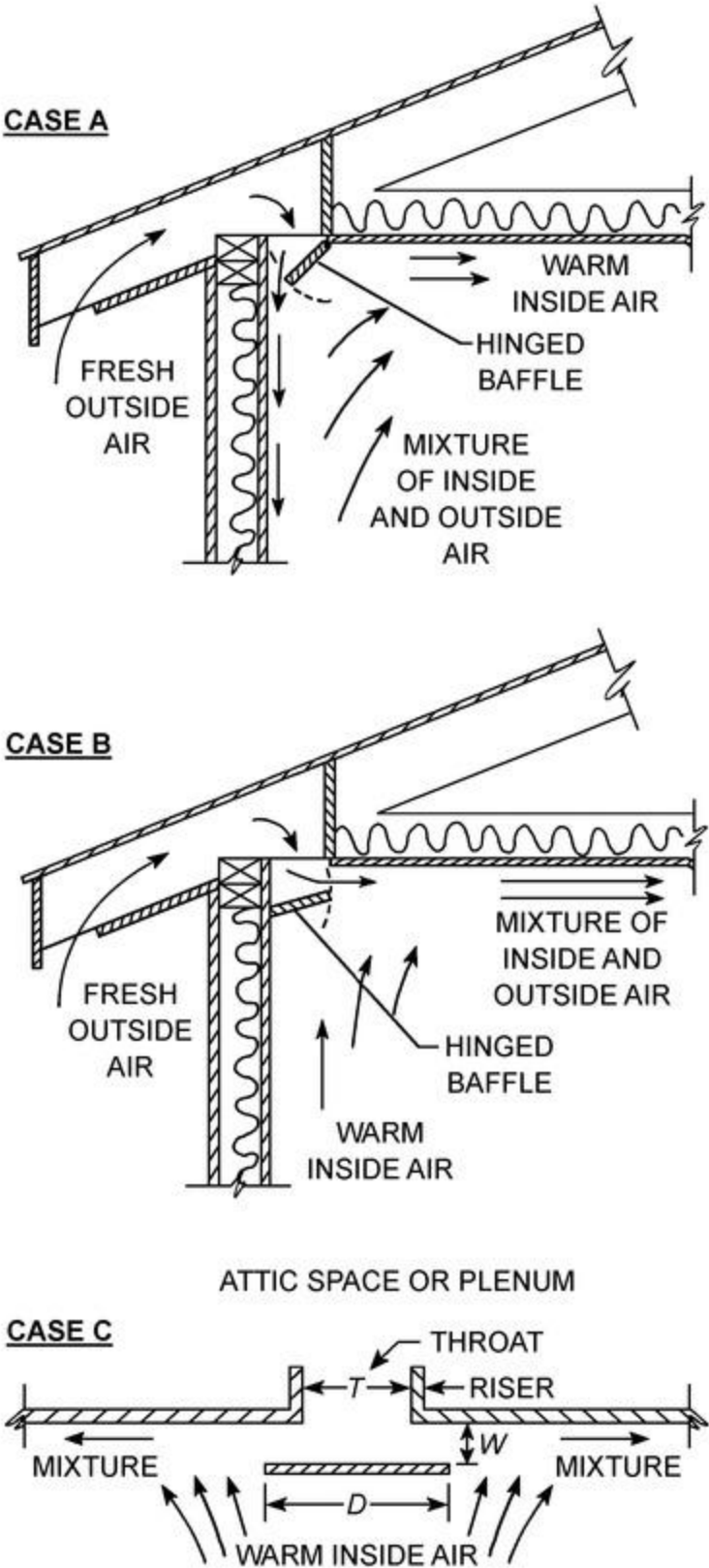


Figure 5. Typical Livestock Building Inlet Configurations

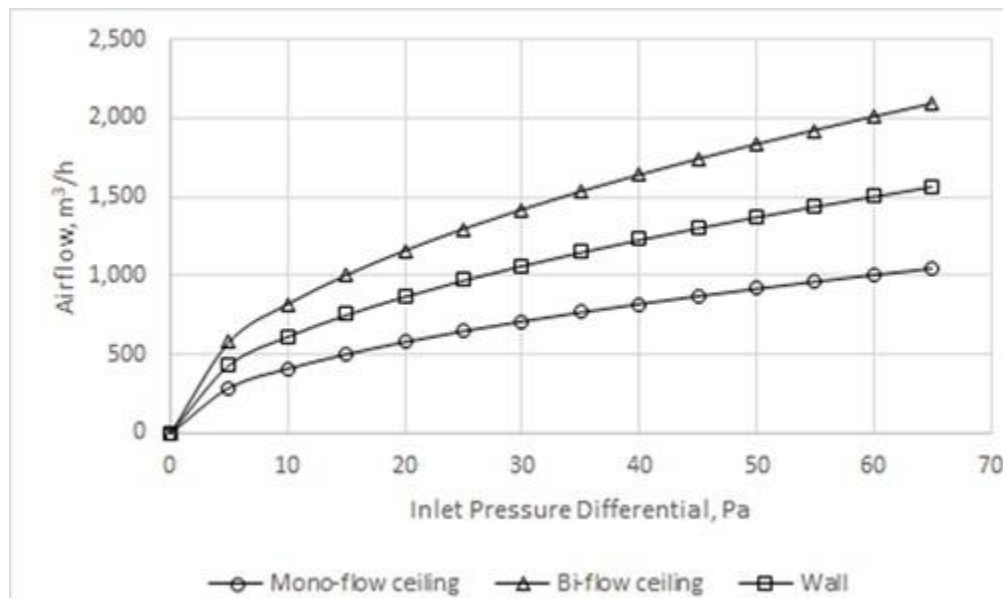


Figure 6. Example of Mono-Flow Ceiling (One Open Baffle; $C_d = 0.60$), Bi-Flow Ceiling (Two Open Baffles; $C_d = 0.60$), and Wall (One Open Baffle, $C_d = 0.90$) 24 in. long inlet open 3 in.

This early work paved the way for the development of commercially available animal housing inlet systems by relating airflow path through an inlet to its efficiency. Comparing Cases A and B indicates substantial differences in airflow efficiency (measured as discharge coefficient C_d), with Case A ($C_d = 0.85$) being more efficient than Case B ($C_d = 0.55$), indicating the consequences of multiple airflow path directions through an inlet system. Commercially available wall and/or ceiling (mono- or bi-flow) inlets are selected for capacity and placement requirements. A wide variety of well-designed and tested inlets are available for the designer that cover most all inlet design needs. [Figure 6](#) compares an “average” commercially available mono-flow ceiling, bi-flow ceiling, and wall inlet.

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 and inlets 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. For inlets, allowances must be made for additional unplanned inlet area from infiltration.

Zhang and Barber (1995) measured infiltration rates of five rooms in a newly built swine building at $0.6 \text{ L/(s}\cdot\text{m}^2)$ 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 $0.6 \text{ L/(s}\cdot\text{m}^2)$ of surface area, the infiltration represents 1.4 ACH (Zhang and Barbert 1995). Lopes et al. (2010) measured infiltration rates from 14 broiler houses and found that, at 25 Pa, infiltration rates that varied from 2.4 to 5.6 ACH and, at 250 Pa from 3.7 to 7.1 ACH. Jadhav et al. (2018) measured infiltration rates from 17 various styles of swine finishing rooms ranging in building age from 2 to 22 years. At a 20 Pa pressure difference across the room envelope, the average total infiltration rate was 5.96 ± 1.49 ACH. Infiltration through curtains was 1.49 ± 1.00 ACH (about 25% of total), through non-operating shuttered fans was 1.52 ± 1.38 ACH (about 26% of total), and the remaining 2.90 ± 1.42 ACH (about 49% of total) from unknown locations (e.g., cracks around closed inlets, ceiling panel joints, wall-to-ceiling junctions). In the heating season, the minimum ventilation is usually about 6 ACH, depending on animal density and maturity level. Thus, large infiltration rates greatly reduce the airflow from the planned and controlled inlet system and can adversely affect the air distribution.

An example field measured results from a curtain-sided $58.5 \times 12.2 \times 2.44 \text{ m}$ swine finishing barn and identified the balance between fans, inlets, and infiltration using a system characteristic curve. [Figure 7](#) plots a commercially available 910 mm diameter axial fan (percent of free-stream airflow) against 10 commercially available bi-flow ceiling inlets ($C_d = 0.70$; percent of fan free-stream airflow). Added to the planned ceiling inlet system is the field measured total infiltration from one of the barns studied in Jadhav et al. (2018). The added leakage area from infiltration, combined with the planned ceiling inlet system, has significantly reduced the operating pressure across the inlet system, compromising adequate fresh-air distribution. Hoff and Jadhav (2019) provide a detailed analysis of infiltration levels and the influence on the planned inlet system performance and overall fresh air distribution. All attempts should be made to reduce leakage area through a series of blower door tests using a FANS unit (Gates et al. 2004).

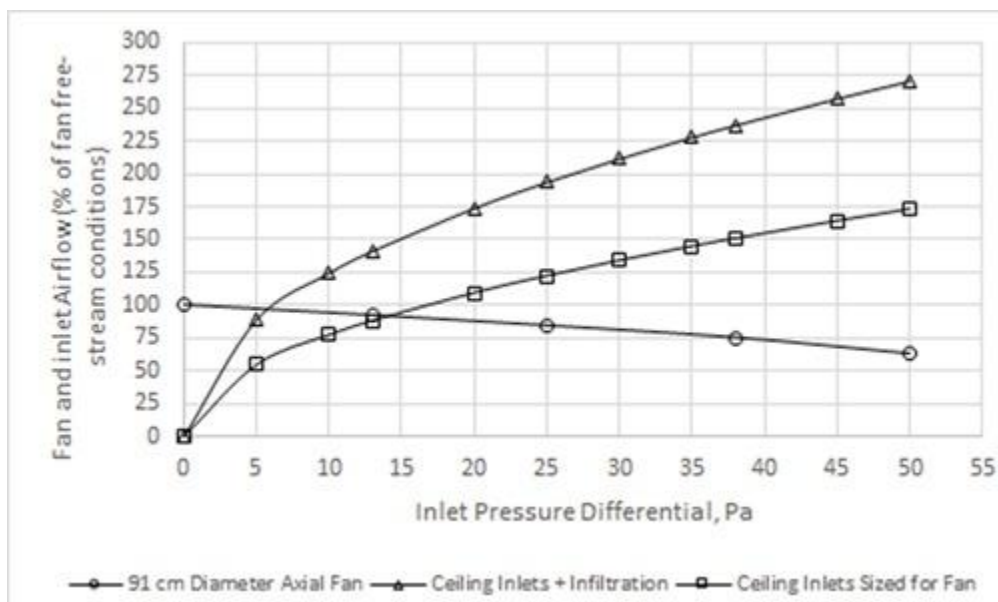


Figure 7. Example commercially available 91 cm diameter axial fan curve (o) against ten commercially available bi-flow ceiling inlets (□) and these inlets combined with total infiltration (Δ) From a 58.5 m × 12.2 m × 2.44 m swine finishing facility. Total infiltration measured from one of the barns in Jadhav et al. (2018).

Room Air Velocity. The average air velocity inside a ventilated structure relates to the inlet air velocity, inlet type (mono-flow ceiling, bi-flow ceiling, wall, etc.), building width, obstructions, and ceiling height. Estimates of air velocity within a barn, based on air exchange rates, may be very low because of 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 air-jet throw distance less than 6 m from general inlets (wall or ceiling) and less than 3 m from perforated tubes.

Fans

Most fans used in animal production facilities are axial. These fans rarely direct air through ductwork and instead are designed for high volumetric output at lower static pressures. 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 can be used to reduce the effects of wind.

Third-party test data should be used to obtain fan performance and energy efficiencies for fan selection (BESS Lab 2022). Fans should be tested with all accessories (e.g., louvers, guards, hoods) in place, just as they will be installed in the building. Accessories have a major effect on fan performance. For larger belt-driven fans, typically used in warmer weather, periodic checks on belt tightness should be made.

Traditionally, many animal production facilities have selected one or two minimum-ventilation fans with multispeed capacity or a variable-frequency drive to manage low-volumetric airflow in cold weather, and the majority of fans for warm and hot weather as single-speed fans with either a belt or direct drive from the motor to the propeller. Recently, some animal production facilities have begun using fans with electronically commutated (EC) motors to replace AC motors, avoiding the need for variable-frequency drives as well as providing energy efficiency at lower motor speeds.

Flow Control. Because 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) using multispeed fans [larger fans (400 W and up) with two flow rates, the lower being about 60% of the maximum rate]; and (4) using variable-speed fans (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 to increase air movement in combination with doors, walls, or windows being opened for natural ventilation.

Sensors and Controls

A traditional control system uses temperature as feedback to adjust ventilation, activate heaters or cooling, and control the opening of planned inlets. As technology has advanced, modern control systems feature the same principles, but can also use feedback on relative humidity, static pressure, and/or gases (e.g., ammonia or carbon dioxide) to adjust ventilation.

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 automatic standby electric generators are highly recommended. Many alarms detect failure of the ventilation. These alarms range from inexpensive power-off alarms to ones that sense temperature extremes and certain gases. Automatic telephone- or cellular-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. Often these warning systems are also tied to backup power systems (generators) to ensure ventilation, feed, and water delivery can be maintained.

2.5 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 8](#) illustrates animal production response to temperature.

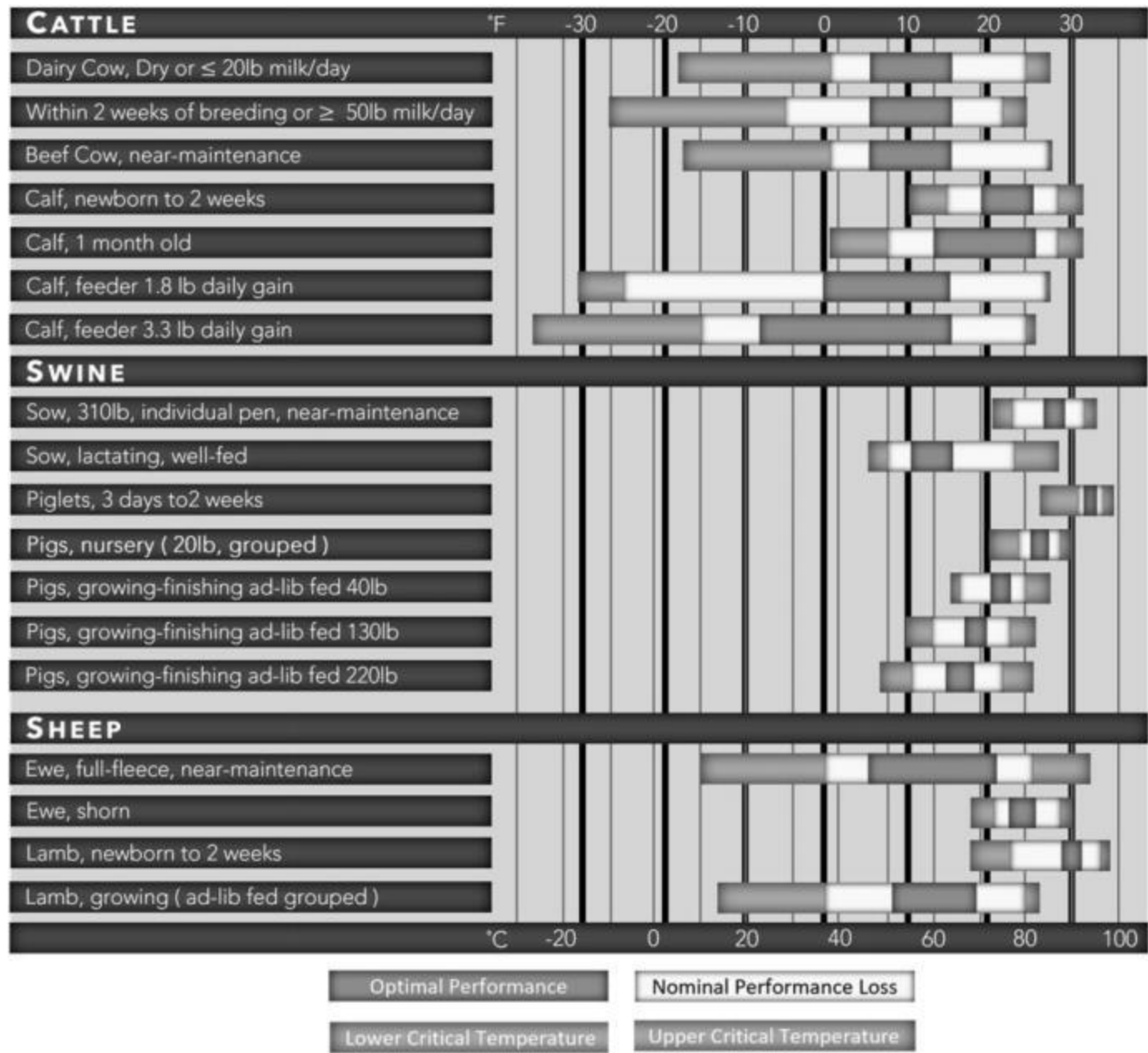


Figure 8. Critical Ambient Temperatures and Temperature Zone for Optimum Performance and Nominal Performance Loss in Farm Animals (Adapted from Hahn 1985, in *Stress Physiology in Livestock*, Vol. II,

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 for cows confined to stalls are 5 to 7 m² per cow. In free-stall housing, cattle are not confined to stalls but can move freely. Space requirements per cow using free-stall housing are 7 to 9 m². 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. 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 often 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 ACH 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, although more controlled naturally ventilated beef housing is gaining popularity.

Swine

Swine housing can be grouped into four general classifications:

1. Farrowing: piglets, from birth to weaning at 7 kg, and lactating sows
2. Nursery: from 14 to 34 kg
3. Grow-finish: from 34 kg to 118 to 136+ kg
4. Wean-finish: from 7 kg to market size
5. Breeding and gestation: primiparous and multiparous sows, boar studs
6. Boar Studs:

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**:

- Temperature: 10 to 20°C, with small areas for piglets warmed to 28 to 32°C by 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 m² per sow and litter (stall); 6.0 m² 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 m² per pig, 5.5 to 14 kg each
0.28 to 0.37 m² 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 350 (150 kg), 6 to 160 L/s
Boar/breeding sow (180 kg), 7 to 230 L/s
- Space:
0.55 m² per pig, 34 to 68 kg each
0.75 m² per pig, 68 to 100 kg each
1.3 to 2.2 m² 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 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 outdoor 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 m² 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 m² 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 m² 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 depend 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 (Clough 1982; Lindsey et al. 1978; McPherson 1975; Moreland 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 16](#) for additional information on laboratory animal facilities.

In the United States, recommended environmental conditions within laboratory animal facilities are usually dictated by Institute for Laboratory Animal Research (ILAR 2010). 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 minimized. 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 (2010) recommendations for room ventilation rates of 10 to 15 ACH are an attempt to provide adequate ventilation for the room and 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, which provide a protective barrier for rodents and reduce airborne infections and diseases, especially neonatal diarrhea, 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/m³ 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 in the same room were found to have significant variation (Riskowski et al. 1996): ammonia levels varied from 0 to 45 mg/m³, air temperature varied from 0.5 to 4 K higher than room temperature, 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 ACH but had no differences in room or cage environmental parameters.

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 placing cages in mass air displacement units reduces contaminant production by keeping litter drier. Using localized contaminant 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 than 80%. High animal activity levels release large quantities of particulates into the air, so management strategies to reduce agitation of animals are helpful.

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 . Riskowski 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 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 the macroenvironment, 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 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/m³, 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/m³ (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 because of the higher temperatures in the low-level exhaust cases when compared to the ceiling and high-level exhausts. The room concentrations of CO₂ and ammonia do not show that any type of supply or exhaust is significantly better or worse than the other type.

3. DESIGN FOR PLANT ENVIRONMENTS

Greenhouses, indoor plant environments (IPEs) such as indoor farms without sunlight, plant growth chambers, and other facilities for indoor crop production overcome adverse outdoor environments and provide conditions conducive to economic crop production. The basic requirements of crop production in a controlled environment setting are (1) adequate light; (2) favorable temperature and humidity; (3) favorable air or gas content; (4) protection from insects and disease; and (5) suitable growing media/substrate and moisture content. Greenhouses have a lower cost per unit of usable space than indoor farms without sunlight.

3.1 GREENHOUSES

[Figure 9](#) shows the structural shapes of typical commercial greenhouses. Other greenhouses may have Gothic arches, curved glazing, or simple lean-to shapes. There are several options for the greenhouse cover material, or glazing, including glass, glass fiber, plastic film, and rigid plastic (see [Table 2](#)). New greenhouse glazing materials, such as ethylene tetrafluoroethylene (ETFE) and transparent solar cells are also available. High light transmission through the glazing is usually important; good location and orientation of the house are also important in providing desired light conditions.

Location affects greenhouse orientation; cooling and heating requirements; the need for supplemental lighting; exposure to plant disease, pests, and air pollution; material handling requirements; and access to labor. 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. In the northern hemisphere, single-span greenhouses located in southern latitudes have more uniform sun exposure when oriented north-south. In northern latitudes, orienting the greenhouse east-west improves sunlight exposure in the winter and can help reduce heating costs due to higher solar heat gains. A good example is the passive solar greenhouse, also known as the Chinese-style solar greenhouse (CSG), which minimizes heating needs in northern latitudes by orienting the greenhouse east-west, with the transparent glazing on the top and south and north sides well insulated or built into an earthen bank. CSGs can be used to grow winter vegetables without auxiliary heating even when the outdoor temperature is below −10°C.

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.

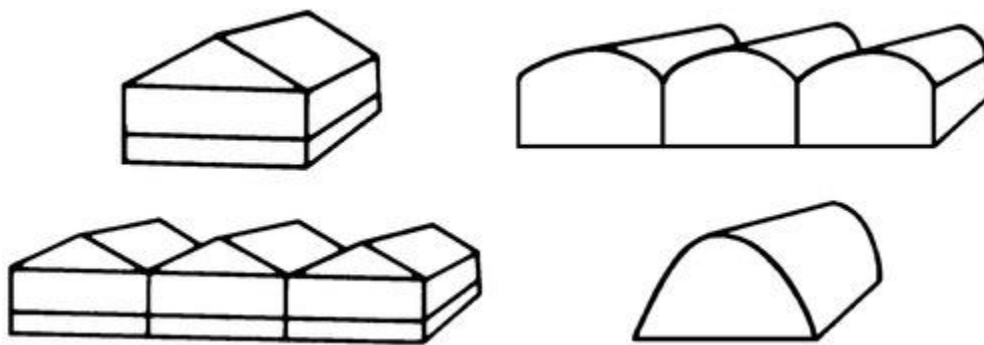


Figure 9. Structural Shapes of Commercial Greenhouses

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 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 build-up 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 allows 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 10](#)). A slope with a 1:2 rise-to-run ratio is the usual inclination for a gable roof.

Ventilation

Mechanical (Forced) Ventilation. Air velocity through the inlets of a greenhouse should range between 1.0 and 2.0 m/s to facilitate good air velocities into the greenhouse and prevent high pressure drops. Air exchange rates between 0.75 and 1 change per minute (ACM) effectively control the temperature rise in a greenhouse. As shown in [Figure 11](#), 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.

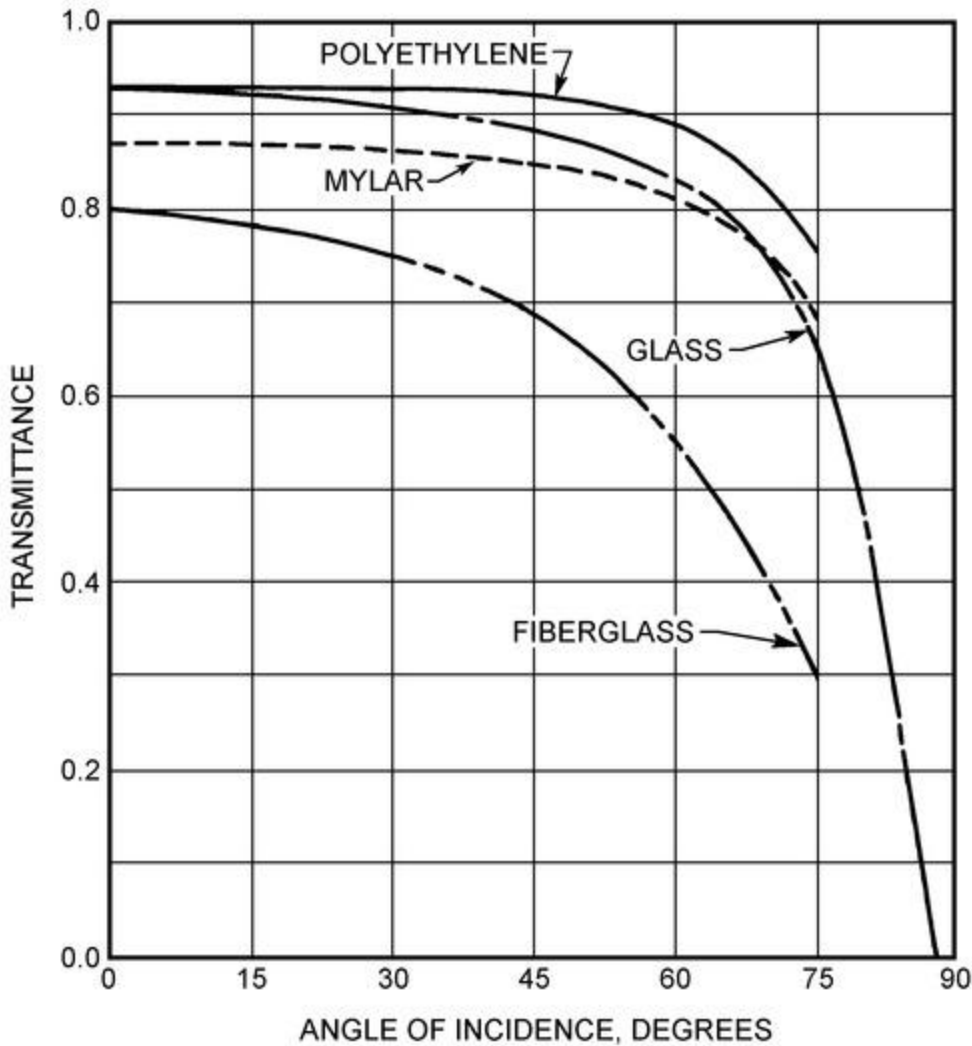


Figure 10. Transmittance of Solar Radiation Through Glazing Materials for Various Angles of Incidence

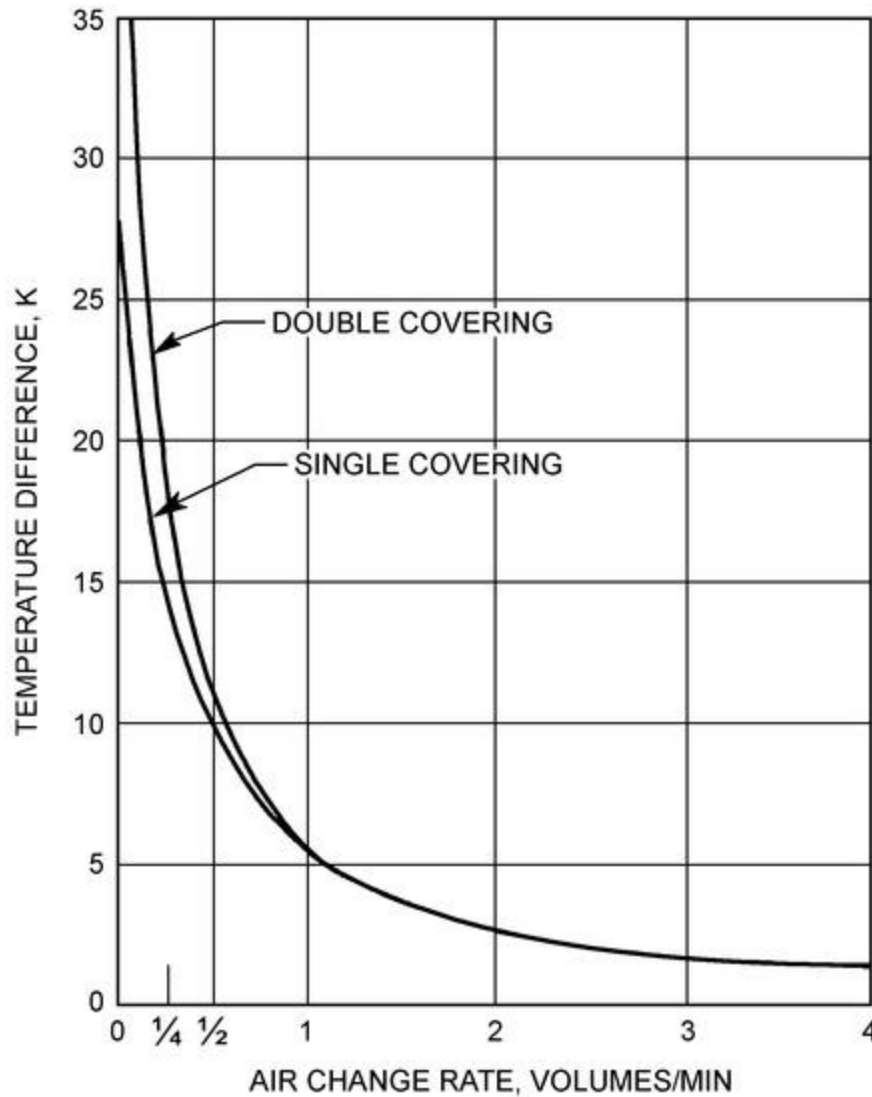


Figure 11. Influence of Air Exchange Rate on Temperature Rise in Single- and Double-Covered Greenhouses

Natural Ventilation. Greenhouses provide natural ventilation using openable ridge vents that run continuously along the roof and openable sashes along the sidewalls. The roof vents are hinged at the ridge, and the wall sashes are hinged at the top of the sash. During the winter and on cold mornings, vents can be opened to effectively cool and dehumidify the greenhouse without operating fans. For a single-span greenhouse, the combined area of the sidewall vents should be equal to that of the roof vents. In ranges of several gutter-connected greenhouses, the sidewall area cannot equal the roof vent area.

Cooling and Heating Loads

Design Conditions. Plan 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.

Structural Heat Loss and Gains. Estimates for heating and cooling a greenhouse consider conduction, infiltration, and ventilation energy exchange. In addition, the calculations must consider solar energy gains 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.

$$q_t = q_c + q_i \quad (4)$$

$$q_c = UA(t_i - t_o) \quad (5)$$

$$q_i = 0.5VN(t_i - t_o) \quad (6)$$

where

U = overall heat loss coefficient, $W/(m^2 \cdot K)$ (Tables 2 and 3)

A = exposed surface area, m^2

t_i = indoor temperature, $^{\circ}C$

t_o = outdoor temperature, $^{\circ}C$

V = greenhouse internal volume, m^3

N = number of air exchanges per hour ([Table 4](#))

Table 2 Suggested Heat Transmission Coefficients

	U , $Btu/h \cdot ft^2 \cdot ^{\circ}F$
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, typically made of polycarbonate.

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 .

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.

Radiation Energy Exchange. Solar gain can be estimated using the procedures outlined in [Chapter 18 of the 2021 ASHRAE Handbook—Fundamentals](#). As a guide, when a greenhouse is filled with a mature crop of plants, about 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. Some research greenhouses use a retractable horizontal heat curtain to reduce the effect of night sky losses. Normally, radiation energy exchange is not considered in calculating the design heat load.

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 wears away during the summer and leaves 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 orated 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. The most common method of cooling a greenhouse is evaporative cooling

Pad-and-Fan Systems. Fans for pad-and-fan 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- and wet-bulb temperatures, or to 1.5 to 2 K above the wet-bulb temperature. The principles of applying evaporative cooling are explained in [Chapter 41 of the 2020 ASHRAE Handbook—HVAC Systems and Equipment](#) and in [Chapter 52](#) of this volume.

The empirical base rate of airflow is 40 L/(s·m²) of floor area. This flow rate is modified by multiplying it by factors for elevation (F_e), maximum interior light intensity (F_l), and allowable temperature rise between the pad and fans (F_t). These factors are listed in [Table 5](#). The overall factor for the house is given by the following equation:

$$F_h = F_e F_l F_t$$

(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.

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.

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

Elevation(Above Sea Level)		Max. InteriorLight Intensity		Fan-to-PadTemp. 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 Pad-and-Fan 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,* fpm
Corrugated cellulose, 4 in. thick	250
Corrugated cellulose, 6 in. thick	350

* Speed may be increased by 25% where construction is limiting.

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

* Speed may be increased by 25% where construction is limiting.

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 build-up 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.

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

High-Pressure Fog (HPF) Systems. 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. An important consideration with HPF systems is that they generally rely on indoor air for evaporative cooling. Therefore, if the air inside the greenhouse is cool and humid, water droplets will not evaporate as quickly or effectively compared to using warmer, drier air.

A line of nozzles placed along the top of the vent opening can cool the entering outdoor 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 cools satisfactorily with less airflow than pad-and-fan 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.

Heating

Greenhouses may have a variety of heaters to manage the air temperature around plants. Outdoor weather conditions affect temperature distribution and heating requirements. Windy conditions increase convective heat losses across the greenhouse glazing. Accumulation of snow can cause the roof to fail without snow melt system. Hail can also damage the greenhouse glazing.

Heating Systems.

Steam or Hot Water Heating. Convection heaters circulate hot water or steam through a 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 12](#). 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 build-up 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.

Overhead Unit Heaters. Overhead unit heaters, whether hydronic or direct fired, often use natural gas or propane and are common in greenhouses. Unit heaters do not provide the most uniform temperature at the plant level and throughout the greenhouse, unless properly located and aimed. 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 airflow (HAF) fans or circulators.

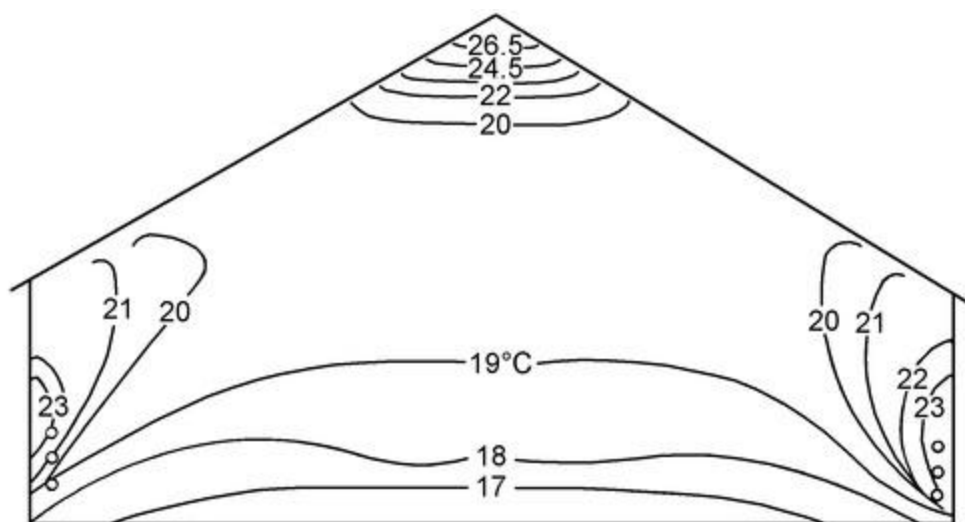


Figure 12. Temperature Profiles in Greenhouse Heated with Radiation Piping along Sidewalls

When direct combustion heaters are used in the greenhouse, combustion gases must be adequately vented to the outdoors 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 mm² of free area per kilowatt input rating of the unit, with a minimum of 0.65 m² for each opening, whichever is greater, is recommended. Unvented direct-combustion units should not be used inside the greenhouse.

Overhead Tube Heaters. 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 (underbench) heaters 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 20 mm plastic pipe spaced 300 to 400 mm on center, and covered with 100 mm of gravel or porous concrete. Hot water, not exceeding 40°C, circulates at a rate of 0.13 to 0.15 L/s per loop. Pipe loops should generally not exceed 125 m in length. This can provide 50 to 65 W/m² from a bare floor, and about 75% as much when potted plants or seedling flats cover most of the floor.

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 underbench 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%.

Many greenhouses combine overhead and perimeter heating. Regardless of the type of heating, it is common practice to calculate 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.

Heat Pumps. 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. They can be used for heating, cooling, and dehumidification.

Radiant (Infrared) Heating. Radiant heating is used in some limited applications for greenhouse and livestock heating. In greenhouses, steel pipes spaced at intervals and heated to a relatively high temperature by special gas heaters can 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.

Direct combustion heaters with a reflector shield can be used in both greenhouse and livestock heating. They are used to warm the ground of housing for young livestock and poultry. They can also be used to radiantly heat the top of the plant canopy in nurseries for bedding plants.

Radiant heat can also be provided by large high-intensity discharge (HID) lamps to allow livestock, especially poultry, to self-select their preferred temperature. In northern climate greenhouses, HID lamps used for supplemental lighting can provide a secondary source of heat to the canopy.

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

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. Plants also continue transpiring, releasing water vapor into the greenhouses. Providing low volumes of ventilation helps maintain inside carbon dioxide levels and remove excess water vapor. A typical rate of airflow for winter ventilation is 10 to 15 L/(s·m²) of floor area or 1 to 5 ACH.

Shade Screens. Shade screens can be used to reduce the solar heat gain to the greenhouse and help avoid heat stress by plants. Shade screens have reflective materials and an open-weave structure to allow sunlight and airflow through. Shade screens can be located inside or outside the greenhouse, can be permanently installed or automatically or manually moveable. A reflectivity value of about 30% is usually acceptable for blocking solar radiation and allowing light penetration to the plants.

Thermal Blankets. Thermal blankets and heat curtains for energy conservation can be used to reduce both convective and radiant heat losses from the greenhouse when it is cold and dark outside. Although this energy savings may be considered in the annual energy use, it should not be used when calculating design heat load; usual practice is to open the heat curtains during snowstorms to facilitate snow melting, thereby nullifying its contribution to the design heat loss value.

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 used to cover vent inlets and outlets. These fine-mesh screens increase 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.

Carbon Dioxide Enrichment. Carbon dioxide is added in some greenhouse operations to increase growth and enhance yields. However, CO₂ enrichment is practical only when little or no ventilation is required for temperature control. Carbon dioxide can be generated from solid CO₂ (dry ice), bottled CO₂, and misting carbonated water. Bulk or bottled CO₂ 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 available CO₂. One study found an air speed of 0.5 m/s to be equivalent to a 50% enrichment in CO₂ without forced air movement.

Lighting

Radiant Energy. Light is normally the limiting factor in greenhouse crop production during the winter. North of the 35th parallel (in the northern hemisphere), light levels are especially inadequate or marginal in fall, winter, and early spring. Supplemental electric light sources may be added to greenhouses to supplement low natural light levels. High-intensity discharge (HID) lamps, such as high-pressure sodium (HPS), metal halide (MH), low-pressure sodium (LPS), and, occasionally, mercury lamps coated with a color-improving phosphor, are often used. Light-emitting diodes (LEDs) are becoming more popular in greenhouses to supplement light in specific wavelengths, extend day lengths, or minimize heat gains associated with HID lighting. Because 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 [$\mu\text{mol}/(\text{s} \cdot \text{m}^2)$] of HPS, MH, LPS, and other lamps to the irradiance (W/m²).

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

Table 9 Constants to Convert to W/m²

Light Source	klx	$\mu\text{mol}/(\text{s} \cdot \text{m}^2)$
400 to 700 nm (photosynthetic active radiation [PAR])		
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

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 because of 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 interrupt 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.

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

Plant and Stage of Growth	W/m ²	Duration	
		Hours	Time
African violets	12 to 24	12 to 16	0600-1800
early-flowering			0600-2200
Ageratum	12 to 48	24	
early-flowering			
Begonias—fibrous rooted	12 to 24	24	
branching and early-flowering			
Carnation	12 to 24	16	0800-2400
branching and early-flowering			
Chrysanthemums	12 to 24	16	0800-2400
vegetable growth branching and multiflowering	12 to 24	8	0800-1600
Cineraria	6 to 12	24	
seedling growth (four weeks)			
Cucumber	12 to 24	24	
rapid growth and early-flowering			
Eggplant	12 to 48	24	
early-fruiting			
Foliage plants	6 to 12	24	
(Philodendron, Schefflera) rapid growth			
Geranium	12 to 48	24	
branching and early-flowering			
Gloxinia	12 to 48	16	0800-2400
early-flowering	6 to 12	24	
Lettuce	12 to 48	24	
rapid growth			
Marigold	12 to 48	24	
early-flowering			
Impatiens—New Guinea	12	16	0800-2400
branching and early-flowering			
Impatiens—Sultana	12 to 24	24	
branching and early-flowering			
Juniper	12 to 48	24	
vegetative growth			
Pepper	12 to 24	24	
early-fruiting, compact growth			
Petunia	12 to 48	24	
branching and early-flowering			
Poinsettia—vegetative growth	12	24	
branching and multiflowering	12 to 24	8	0800-1600
Rhododendron	12	16	0800-2400
vegetative growth (shearing tips)			
Roses (hybrid teas, miniatures)	12 to 48	24	
early-flowering and rapid regrowth			
Salvia	12 to 48	24	
early-flowering			
Snapdragon	12 to 48	24	

early-flowering			
Streptocarpus	12	16	0800-2400
early-flowering			
Tomato	12 to 24	16	0800-2400
rapid growth and early-flowering			
Trees (deciduous)	6	16	1600-0800
vegetative growth			
Zinnia	12 to 48	24	
early-flowering			

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.

Energy Saving Strategies

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 allow use of the most inexpensive fuel available.

Energy Recovery and Generation. When available, heat recovery can be used as a possible source of winter heat. Solar thermal energy systems are not typically used at a commercial scale. 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. 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.

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 outdoor 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 enough 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 preceding methods 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. 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 obstruction are more important than the kind of material used. Some films are vaportight and retain moisture and gases. Others are porous and allow 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; this design 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 irradiance level and whether it is snowing, rather than on 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 from shading by the blanket when it is not in use during the day.

Other Recommendations. Although 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.

Sensors and Controls

Temperature and humidity sensors should be located at the top of the plant canopy, preferably in a shielded apparatus that protects the sensors from radiation, including direct sunlight. A vented sensor shield will also improve the accuracy of readings. Temperature and humidity readings are used to control ventilation, cooling, and heating systems. A **photosynthetic active radiation (PAR)** light sensor at the top of the canopy can be used to control automated shading systems and supplemental lighting sources. A CO₂ sensor can be used to control the operation of CO₂ burners and liquid CO₂ injectors. An exterior weather station that monitors temperature, relative humidity, solar radiation, wind direction and speed can be useful in predicting greenhouse conditions and managing equipment operation before changes are observed inside the greenhouse.

3.2 INDOOR PLANT ENVIRONMENTS WITHOUT SUNLIGHT

Indoor plant environments (IPEs) without sunlight are characterized by structures that have an opaque envelope and a reliance on electrical lighting for plant photosynthesis. IPEs have irrigation systems to manage water and nutrient delivery, HVAC systems to control temperature and relative humidity, and other systems that can be used to manage CO₂ concentration, air distribution, and air quality. There are many types of IPE facilities, including single-level indoor farms (SIFs), vertical farms (VFs), controlled-environment rooms (CERs), container farms (CF) and growth chambers.

Construction and Materials

The exterior building materials for a commercial-scale IPE should meet or exceed the minimum envelope requirements according to the local governing building codes. The interior surfaces of the grow rooms should have a water vapor barrier to help prevent water migration into the building materials, which can degrade construction materials, increase the risk for mold growth, and reduce controllability of room humidity.

Wall insulation for a growth chamber environment should have a thermal conductance of less than 0.15 W/(m² · 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 require periodic replacement.

Floors and Drains

Floors and floor drains should be corrosion resistant, smooth, and easy to wash down and clean. Tar or asphalt waterproofing materials and volatile caulking compounds should not be used because they are likely to release phytotoxic gases into the grow room air. The floor must have floor drains to remove overflowing water, spills, and nutrient solutions. The drains should be trapped and equipped with screens to catch plant and substrate debris.

Sensors and Controls

IPEs 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 condensers are remotely located.
- Control of the CO₂ level in enriched environment chambers.
- 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 controls are widely used for programming, controlling, and monitoring the IPE conditions. Host systems are also used to program and monitor larger numbers of units in a common facility, and most offer remote access functions. Host systems tend to be vendor-specific in their use and application.

3.3 COMMERCIAL INDOOR FARMS

Planting Benches and Support Structures

Plants may be grown in containers filled with soil, inert media (such as coco coir), glass fiber cubes (e.g., rockwool), or other substrate. SIFs typically support plants on benches or tables that are elevated about 1 m above the finished floor. This height allows easy access to the plants for transplanting, pruning, harvesting, scouting for insects, and other maintenance activities. VFs often grow plants on multi-level racks that are stacked on top of each other, leaving enough vertical space for plants to grow. LED lights are attached to the bottom of the rack above plants. Other VFs use A-frame structures or other vertical hanging surfaces with plants growing out of the side and irrigation water gravity-fed from top to bottom.

Racking systems and benches may be stationary or moveable on sliding rails. Moveable benches increase the usable production area, while providing accessible aisles when moved from side to side. The benches are usually rated for loads of at least 245 kg/m². The bench should be constructed of nonferrous, perforated metal, wire, 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.

Design Conditions

Commercial SIFs and VFs are typically operated at air temperatures ranging between 18 to 30°C and a coincidental relative humidity ranging between 50 and 80%, depending on the crop species, age, and time of day. Vapor pressure deficit (VPD), used by growers to manage plant transpiration and nutrient delivery, is the difference between the theoretical pressure exerted by water vapor held in saturated air (100% rh at a given temperature) and the pressure exerted by the water vapor that is actually held in the air being measured at the same given temperature (i.e., the difference between the vapor pressure inside the leaf to the vapor pressure of the air).

Vegetative plants, such as leafy greens and culinary herbs, have a target VPD of 0.65 to 0.9 kPa. Fruiting and flowering plants, such as tomatoes, cucumbers, and cannabis, typically have a higher target VPD of 1.0 to 1.4 kPa.

Cooling

Cooling is used to manage the temperature of the IPE. Electrical lighting is the primary source of sensible heat gain in the IPE; other sources of sensible heat gain include envelope, ventilation, fan and pump motors, people, and automated equipment. Air conditioning loads for IPEs may require 150 to 315 W/m² depending on the loads from the envelope, lighting, ventilation, and other heat-generating mechanical equipment. Plants generate a high latent cooling load from evapotranspiration, resulting in a sensible heat ratio that typically ranges between 0.25 and 0.6. Recirculation of conditioned air is common to reduce the ventilation loads, contain CO₂ in the plant environment, and provide odors controls for some crops.

Because IPEs without sunlight are operated year-round, cooling is required even during peak heating conditions. Cooling is most commonly provided with equipment using the refrigeration cycle, including split system air conditioners, packaged rooftop DX systems, and chilled water delivered to indoor air handling units. A complete description of these systems, their operation, and design conditions can be found in ANSI/ASABE/ASHRAE *Engineering Practice* 653, HVAC for Indoor Plant Environments without Sunlight. To prevent overcooling of the plants, conditioned air is often supplied 3

to 5.5 K less than the room design target temperature when the lights are on. When lights are off, to counteract the evaporative cooling effect of plants, the supply air may be warmer than the design temperature.

Dehumidification

Plants move water from the roots to the leaves in a process called transpiration. When water reaches the leaves, it evaporates into the air, converting sensible energy from the surroundings into latent energy and raising the room humidity. To manage humidity inside the IPE, dehumidification is required to remove excess water vapor. Dehumidification is most commonly accomplished through the vapor-compression cycle, with evaporator coils set to a temperature below the dew-point temperature of the air. Solid and liquid desiccant dehumidifiers are effective when the dew point target is very low or when electrical power to the site is limited and natural gas is available. When the outdoor dew-point temperature is lower than the target room’s dew point, ventilation can be used to either supplement mechanical dehumidification or provide all moisture removal using air-side economizers.

Heating

Heating the IPE is not often required, unless there are large heat losses through the envelope and ventilation. Heating is primarily required to reheat the air discharged off the evaporator coils when they are used for dehumidification. Reheat can be accomplished through heat recovery, using hot-gas reheat from a DX cooling system or hot water generated from a heat recovery chiller or combined heat and power system. Reheat may also be accomplished with an auxiliary heating source, such as electric resistance, indirect gas-fired furnace, or heat pump. A direct-fired gas furnace is not recommended to avoid introducing combustion gases and water vapor into the IPE. Ethylene from combustion is of particular concern to the health and productivity of plants.

Ventilation Heat Exchangers

For IPEs, the minimal use of ventilation limits the energy savings potential of a heat exchanger unless used to precondition recirculating air.

Air Distribution and Air Velocity

The volume of air distributed through an IPE depends on the cooling and dehumidification requirements, as well as the room geometry. A recommended air turnover rate of 15 to 20 ACH is recommended to effectively condition the entire IPE volume. The target air velocity across the plants ranges between 0.35 to 1.0 m/s, depending on crop age and presence of flowers. Moving air through a VF system can be challenging and often requires air-moving devices (diffusers, circulation fans) at each level where the plants are growing to effectively remove heat and moisture, and deliver CO₂ and conditioned air.

Lighting

The type of light source and number of lamps used in IPEs are determined by the desired plant response and species of plant cultivation. High-intensity discharge (HID) lamps are commonly used in IPEs growing cannabis and other crops that require a high light intensity. In early generation VFs, cool-white fluorescent plus incandescent lamps that produce 10% of the fluorescent illuminance were used. A number of fluorescent lamps have special phosphors hypothesized to meet the spectral requirements of the plant; however, there is little data to suggest that they are superior to cool-white and warm-white lamps.

In new generation SIFs and VFs, light emitting diodes (LEDs) are becoming more prevalent. LEDs have many advantages, including more efficient conversion of power to usable light by plants, less sensible heat generated, dimming capabilities, and spectral tuning to provide specific wavelengths of light specific to the plant species requirements. In VFs, using LEDs allows plants to be grown more closely to the light source and allows more planting levels. The potential downside of using LEDs is the reduced radiant heat transmitted to the plant, which can slow growth. When LED lights are used, it is recommended that the air temperature of the IPE be raised by 1.5 to 7.5 K relative to IPEs using HID lighting. The modified air temperature depends on the proximity of lights to plants, the type of lights used, and the type of plants grown.

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							

A	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	PGA	46	13	13	35	39	13
	Plant growth	PGB	46	15	16	34	37	13
	Infrared	FIR	46	2	9	39	39	13
	High-intensity 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
B	High-pressure sodium	HPS	470	26	36	36	13	15
	Low-pressure sodium	LPS	230	27	31	25	22	22
	Light-emitting diodes*	LED	See manuf.	90-100	95-100	0	0-5	4-6

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

* Power drivers used for LEDs have a heat loss ranging between 4 and 6%.

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

One method to design lighting for biological environments is to base light source output recommendations on photon flux density $\mu\text{mol}/(\text{s} \cdot \text{m}^2)$ between 400 and 850 nm. Rather than basing illuminance measurements on human vision, this allows 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](#).

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. Because 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 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 IPE 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 caused by 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. Because 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.

Fluorescent and metal halide designs should be based on 80% of the initial light level. Most IPE 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 shifts 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.

To maintain a constant distance from plant to light source, light fixtures may be mounted on movable, counterbalanced light banks. Large grow rooms, especially those constructed as an integral part of the building, rarely separate the lamps from the growing area with a transparent barrier.

3.4 PLANT GROWTH CHAMBERS

Plant growth chambers are used to study all aspects of botany. They have floor areas less than 5 m² and 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 CO₂ level. Plant growth chambers are similar to walk-in cold storage rooms, except for the lighting and larger refrigeration system needed to handle heat produced by the lighting.

Some growers use growth chambers to increase seedling growth rate, produce more uniform seedlings, and grow specialized, high-value crops. The main components of the growth chamber 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.

Location

The location for a growth chamber must have space for the outer 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 requires electricity, water, compressed air, and ventilation and exhaust air systems. For planning purposes, electrical densities of up to 1500 W/m² of controlled environment space) are possible, or 1000 W/m² of total space housing growth chambers.

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 245 kg/m². The bench or truck top should be constructed of nonferrous, perforated metal, wire, 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.

Design Conditions

Air-conditioning equipment for relatively standard chambers provides temperatures that range from 7 to 35°C. Specialized growth chambers 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 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 older facilities, the variation is 0.5 to 1 K.

The relative humidity in many growth chamber environments is simply an indicator of the existing psychrometric conditions and is usually between 50 and 80%, depending on the temperature. Complete control of relative humidity requires dehumidification as well as humidification.

Cooling

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.

Humidity Control

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.

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.

Air Distribution

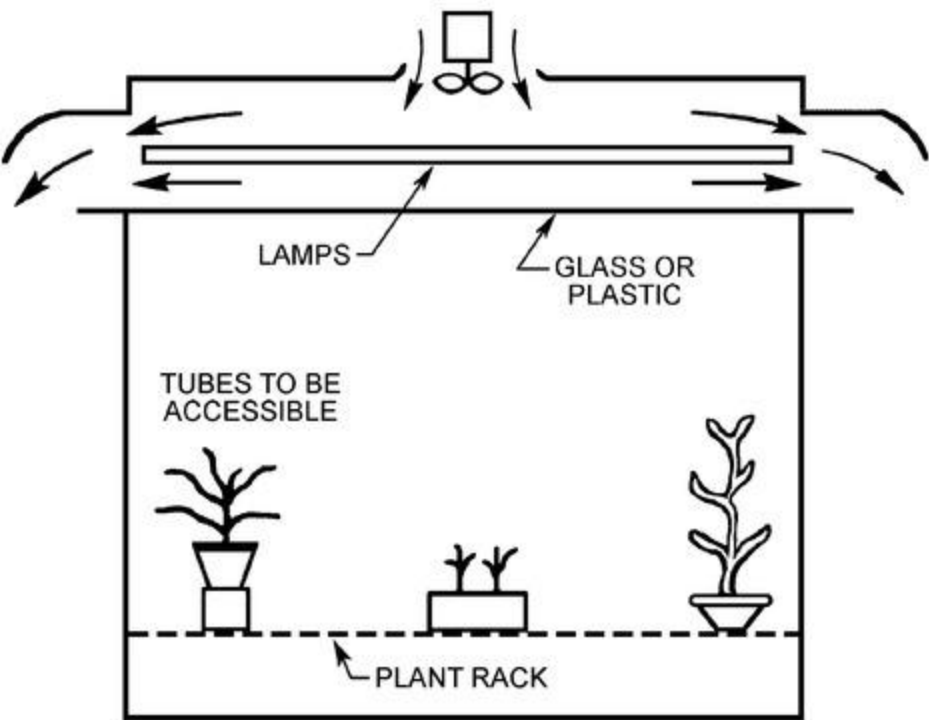
The plant compartment is the heart of the growth chamber. The primary design objective, therefore, is to provide the most uniform, consistent, and regulated environmental conditions possible. Thus, airflow must be adequate to meet specified psychrometric conditions, but it is limited by the effects of 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 some 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 should be kept 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.

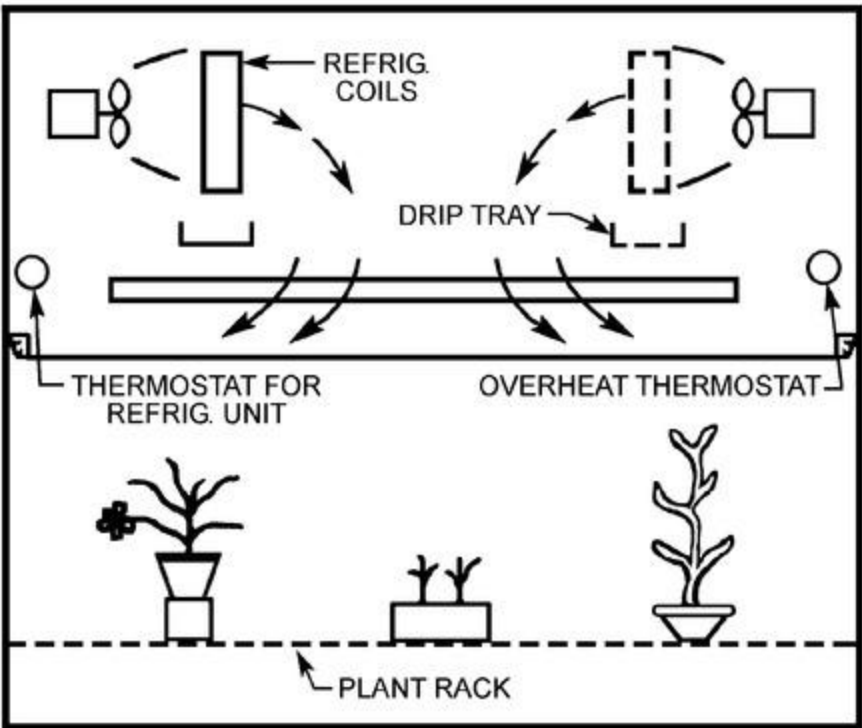
The ducts or false sidewalls that direct air from the evaporator to the growing area should be small, but not so small that the noise increases appreciably more than acceptable building air duct noise. Growth chamber design should include some provision for cleaning the interior of the air ducts.

Lighting

Growth chambers and cabinets often 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 twofold 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 maintains 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 ([Figure 13](#)).



GROWTH CABINET – LIGHTS AIR-COOLED



GROWTH CHAMBER – LIGHTS COOLED BY REFRIGERATION

Figure 13. Cooling Lamps in Growth Chambers

Table 13 Height and Spacing of Luminaires

Light Source	Radiant Flux Density, W/m ²						
	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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/m ² , 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 m ²	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 m ²	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

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 darken plastic, 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 to shut down the lamps if the temperature rises to a critical level.

3.5 PHYTOTRONS

A phytotron is a botanical laboratory comprising a series of chambers reproducing any condition of temperature, humidity, illumination, or other plant growth factor. They are typically found in plant-based research buildings. These facilities require substantial electrical and mechanical systems to generate light required for plant growth as well as to remove heat generated by lights and cooling systems.

Electrical Requirements

If the exact number and size of units is unknown, an electrical consumption of 2 kW/m² may be assumed for lighting input to the phytotron. If the phytotron has a built-in refrigeration system, the compressor input is typically 80% of lighting input, because the units are designed to maintain the chamber at 10°C with lights on, creating a high latent load on the compressor at an inefficient operating point. Remote condensing units and remote air-cooled condensers require a separate electrical feed and interconnecting control wiring.

Heat Rejection

Most of the electrical input to the IPEs is converted to heat. The heat rejection system must be able to remove that heat from the phytotron; this can be done in a number of ways.

If the IPEs are primarily self-contained air-cooled units, the room can be ventilated at a rate that maintains acceptable working conditions in the space (see [Chapter 14](#)). Because of the high ventilation rates needed, ensure that air returned to the space is properly filtered to limit the introduction of dust, pollen, insects, and bacteria from the outdoors.

Self-contained IPEs with water-cooled condensing units typically use a condenser water loop connected to a cooling tower or fluid cooler to reject heat. [Chapter 13 of the 2020 ASHRAE Handbook—HVAC Systems and Equipment](#) describes selection and design of these systems. Because phytotron facilities operate all year, operation of fluid coolers and cooling towers at ambient temperatures below freezing in cold climates must be considered. Sediment must also be removed from the condenser water, because the condenser is a relatively low-velocity point in the loop and will plug up with these solids.

Locations of remote condensing units or remote air-cooled condensers should be easily accessible, because they require servicing at all times of the year. Ensure good airflow around all air-cooled condensers so that discharge air from one unit is not re-entrained into adjacent units. Locate equipment away from laboratory exhaust systems that could accelerate corrosion of metal on the units. Refrigerant piping must be carefully designed, sized, and installed to ensure proper oil return and long-term operation of the compressors. [Chapter 1 of the 2022 ASHRAE Handbook—Refrigeration](#) details these requirements.

Central chilled water can be used. The primary consideration is the chilled-water temperature to be provided to each unit. In practice, most IPEs operate at internal temperatures between 20 and 25°C when lights are on. As a result, standard chilled-water supply temperatures of 7°C can be used successfully. When lights are off, temperatures of 10°C can be achieved using the same chilled-water temperature. Chambers that require cooler daytime temperatures can use water-cooled condensing units and reject their heat to the chilled-water loop. Some phytotrons use chilled-water supply

temperatures of -10°C , but with a high failure rate on the compressors because of low suction temperatures and poor oil return.

Energy Conservation

Because of IPEs’ very high energy consumption and the predictable day/night cycle of the lighting load, consider balancing the units’ schedule to limit electrical demand. Most plants require a 12 to 16 h daily photoperiod. By adjusting the day/night schedule, it is possible to reduce the phytotron’s electrical demand by up to 25%.

Chilled-water systems can have the lowest total energy consumption because of the economy of scale available by using large-capacity chillers versus small compressors. Large laboratory facilities can reject heat from the phytotron to preheat laboratory makeup air. In cold climates, chilled water can be produced without mechanical cooling at ambient temperatures below -2°C . If exposing chilled water to ambient air that could be below freezing, use an appropriate concentration of suitable antifreeze.

Condenser water can also be used to preheat fresh air or, because of its higher temperature, other process loads, such as domestic hot water.

Operating Considerations

IPEs with self-contained compressors generate noise. When a large number of units are placed in a room, consideration should be given to attenuating this sound. Chilled-water and remote-condensing-unit units provide the quietest environment for workers, because the compressors are remotely located. The total installed cost of these systems may be higher because of the extra cost to remotely locate and energize the cooling systems.

Plants require CO_2 to grow. Many IPEs in phytotrons have a central exhaust system to exhaust any chemicals used inside the chambers and to pull in a constant supply of air. Because the units are under a slight negative pressure, makeup air entering the unit must be filtered to limit uncontrolled spread of pollen, insect pests, and bacteria. The flow rate from units depends on the type of crop being grown. A normal rate of ventilation is 10 to 15 L/s per square metre of plant growth area.

Water is required for humidification, plant watering, and cleaning. This often means that three totally separate systems are used. High-purity water is often available in laboratory buildings, and can be used to directly humidify the chambers without introducing waterborne minerals into the chamber. Water for plants should be tempered to avoid root shock. A tempered-water loop with provision for introducing chemical fertilizer, supplied to designated hose stations in the phytotron, is common in larger installations, but normal municipal water supplies are all that is required. Cleaning of these areas is important.

IPEs require drainage of cooling coil condensate and plant overwatering. It is important to provide good drainage near the units without excess use of drain lines running exposed across the floor. Similarly, any piping or ducts that operate below the room design dew-point temperature should be insulated to prevent condensation on those lines. These puddles of water are prime breeding grounds for plant pests, and could cause slip hazards for staff.

Keeping the phytotron clean is important for plants’ health. Phytotrons typically have separate potting areas and harvest rooms, both of which generate a lot of dust and dirt. Potting areas must remain sanitary to minimize contamination of seedlings and plantlets. In harvest rooms, mature plants may host insects that can damage young plants. Ventilation systems should keep harvest rooms at negative pressure relative to the cleaner potting areas and phytotron.

Genetically modified plants must be autoclaved once the plant is harvested. Provision should be made for an autoclave next to the harvest room, with a supply of steam or electricity. Odors and steam from the autoclave should be exhausted out of the building.

3.6 OTHER INDOOR PLANT ENVIRONMENT 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.

Table 14 Mounting Height for Luminaires in Storage Areas

Survival = 3 W/m ²		Maintenance = 9 W/m ²	
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

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/m² and a preferred level of 3 W/m² irradiance for 8 to 12 h daily.

Medium (maintenance): A minimum of 3 W/m² and a preferred level of 9 W/m² irradiance for 8 to 12 h daily.

High (propagation): A minimum of 9 W/m² and a preferred level of 24 W/m² 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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