

CHAPTER 10

ENVIRONMENTAL CONTROL FOR ANIMALS AND PLANTS

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THERMAL conditions, air quality, lighting, noise, ion concentration, and crowding are important in designing structures for animals and plants. Thermal environment influences heat dissipation by animals and chemical process rates in plants. Lighting influences photoperiodism in animals and plants, and photosynthesis and regulation in plants. Air quality, noise, ion concentrations, and crowding can affect the health and/or productivity of animals or plants. This chapter summarizes the published results from various research projects and provides a concept of the physiological factors involved in controlling the environment.

ANIMALS

Animal performance (growth, egg or milk production, wool growth, and reproduction) and their conversion of feed to useful products are closely tied to the thermal environment. For each homeothermic species, an optimum thermal environment permits necessary and desirable body functions with minimum energetic input ([Figure 1A](#)). The optimal thermal environment—in terms of an effective temperature that integrates the effects of dry-bulb temperature, humidity, air movement, and radiation—is less important to the designer than the range of conditions that provides acceptable animal performance, efficiency, well-being, and economic return for a given species. [Figure 1A](#) depicts this range as the **zone of nominal losses**, selected to limit losses in performance to a level acceptable to the livestock manager. Researchers have found that the zone of nominal losses corresponds to the welfare plateau (i.e., welfare is enhanced by maintaining environmental conditions within the zone of nominal losses). Milk and egg production by mature animals also shows an optional thermal environment zone, or zone of nominal losses ([Figure 2](#)).

Developed from actual measurements of swine growth, [Figure 1B](#) shows the relationships of energy, growth, and efficiency with air temperature. In the case of growing pigs in [Figure 1B](#), the range of temperatures from 15 to 22°C, which includes both optimal productivity and efficiency levels, represents acceptable design conditions to achieve maximum performance and efficiency. Even beyond that temperature range, performance and efficiency do not markedly decline in the growing pig until near the lower critical temperature (LCT) or upper critical temperature (UCT), and potential performance losses within the temperature range from 10 to 25°C may be acceptable. Response relation-

ships, as shown in [Figure 1B](#), allow environmental selection and design criteria to be based on penalties to performance (i.e., economic costs) and animal well-being—particularly when used with climatological information to evaluate risks for a particular situation (Hahn et al. 1983). Choosing housing requires caution, because research indicates that factors such as group versus individual penning, feed intake, and floor type can affect the LCT by 5 K.

The limits of acceptable values of the LCT and UCT depend on such effects as the species, breed, genetic characteristics of an individual animal's age, mass, sex, level of feeding and type of feed, prior conditioning, parasites, disease, social factors such as space allocation, lactation or gestation, and physical features of the environment. The LCT and UCT vary among individuals; data reported are for group means. As a result, the limits become statistical values based on animal population and altered by time-dependent factors.

Acceptable conditions are most commonly established based on temperature because an animal's sensible heat dissipation is largely influenced by the temperature difference between the animal's surface and ambient air. Humidity and air movement are sometimes included as modifiers for an effective temperature. This has been a logical development. Air movement is a secondary but influential factor in sensible heat dissipation. The importance of air velocities is species and age dependent (e.g., swine under 8 weeks of age experience slower gains and increased disease susceptibility when air velocity is increased from 125 to 250 mm/s).

With warm or hot ambient temperature, elevated humidity can restrict performance severely. Relative humidity has little effect on the animal's heat dissipation during cold temperatures, and it is usually only moderately important to thermal comfort during moderate temperatures. (Information is limited on such interactions, as well as on the effects of barometric pressure, air composition, and thermal radiation.)

Animals housed in a closed environment alter air composition by reducing oxygen content and increasing carbon dioxide and vapor content. Decomposing waste products add methane, hydrogen sulfide, and ammonia. Animal activities and air movement add microscopic particles of dust from feed, bedding, and fecal material. Generally, a ventilation rate sufficient to remove water vapor adequately controls gases. However, improper air movement patterns, certain waste-handling methods, and special circumstances (e.g., disease outbreak) may indicate that more ventilation is necessary. In many cases, ventilation is not as effective for dust control as for gas control. Alternative dust control strategies may be needed.

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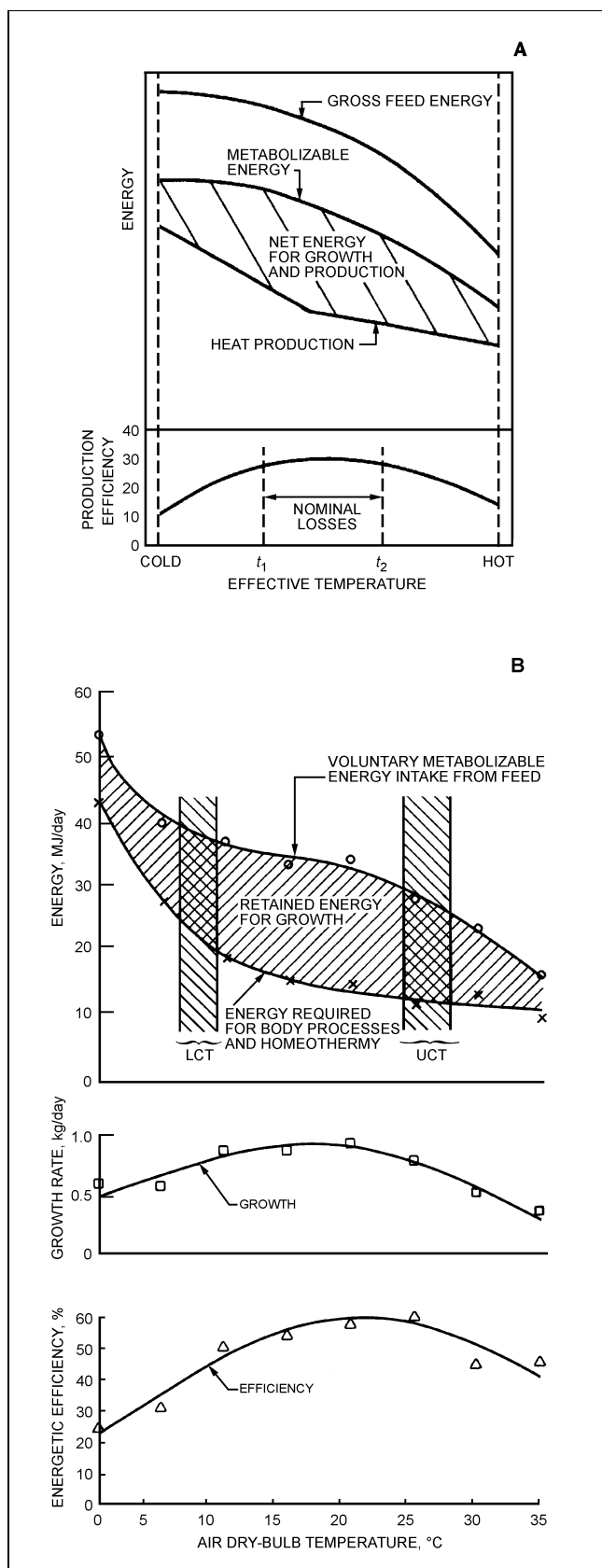


Fig. 1 Energetic and Performance Relationships Typical for Animals as Affected by Effective Environmental Temperatures
(Hahn et al. 1983)

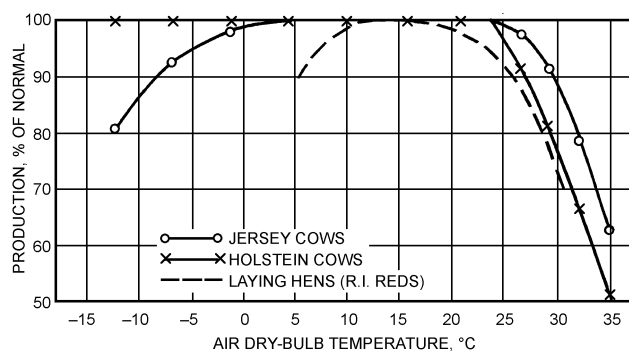


Fig. 2 Comparative Effect of Air Temperature in Mature Animal Production
(Hahn et al. 1983, Tienhoven et al. 1979)

ANIMAL CARE/WELFARE

Animal facilities that facilitate good animal care and welfare must be designed considering a wide range of environmental factors beyond thermal conditions. These include space requirements, flooring type, lighting, feed and water requirements, animal handling, and waste management. Facilities that meet animal care and welfare needs vary considerably by purpose, animal species, and geographic location. For additional information and guidelines for designing animal facilities to meet animal care and welfare needs, see the section on Bibliography.

PHYSIOLOGICAL CONTROL SYSTEMS

An animal has a phenomenally stable control system. Despite wide variations in environmental, nutritional, or pathological conditions, animals can control blood pressure and composition, body temperature, respiration, and cardiac output without conscious effort. Physiological control systems react to unfavorable conditions to ensure survival of the animal at the expense of production or reproduction.

One physiological control system important for air-conditioning design is the homeothermic system—the means by which an animal adapts to its thermal environment. The animal strives to control body temperature by adjusting both heat production in the tissues and transfer of heat to the environment from exposed surfaces. The homeothermic system in domestic animals is a closed-loop system and can be analyzed like any closed-loop control system.

Heat Production

Heat production data have been measured for many farm animals (Yeck and Stewart 1959, Longhouse et al. 1960, 1968, Bond et al. 1959). Much of the early data were obtained for a basal condition (i.e., all life processes at a minimum level). Heat production under conditions of normal metabolic activity is more useful to the engineer. Such data are now available for most farm animals (Figures 3 and 4). Where possible, the data show total or sensible and latent heat for animals fed in a typical housing situation. Thus, the sensible heat used to evaporate urine moisture (assuming no other moisture) appears as latent heat. For design purposes, such data are better reflections of total heat partitioning than metabolic heat production obtained by calorimetry. Scott et al. (1983) provide additional information on specific situations.

The rate of heat production is primarily a function of temperature, animal species, and animal size. Heat production varies diurnally, depending on animal activity and eating times, and may change dramatically under special circumstances (e.g., when animals are disease-stressed). Building type and waste-handling system can affect the conversion of sensible to latent heat by more than 50%. Heat and moisture production of animals changes with other

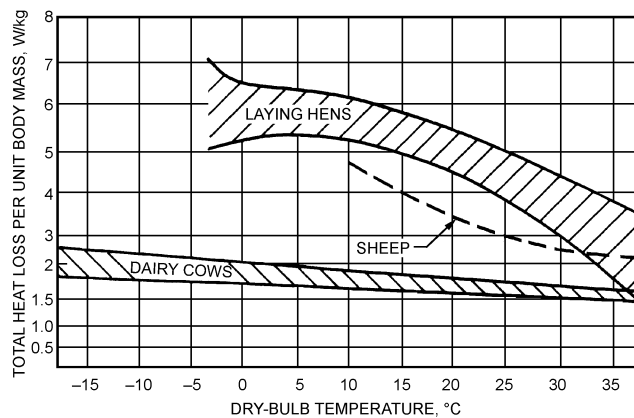


Fig. 3 Comparative Heat Loss of Mature, Producing Animals
(Tienhoven et al. 1979)

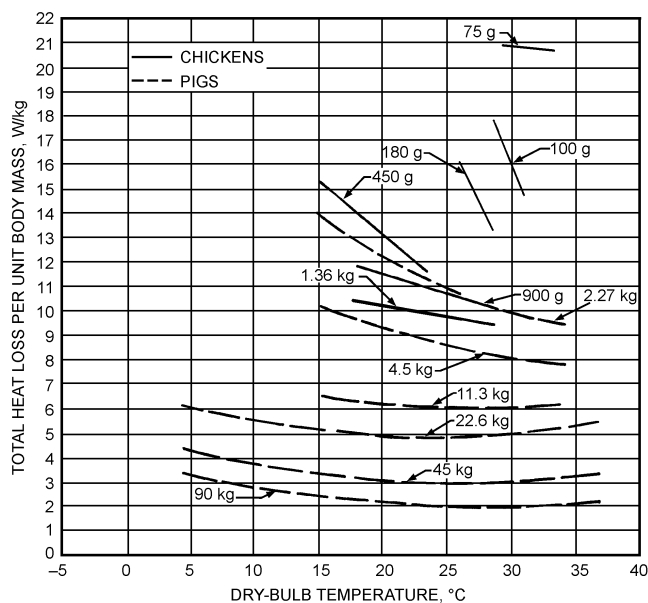


Fig. 4 Comparative Heat Loss of Growing Animals
(Bond et al. 1959)

variables such as their genotype and growth rate. For example, a broiler chicken grows to 4 kg in 7 weeks compared to 12 weeks 30 years ago. Faster growth rate is usually associated with higher heat production, so updated data is needed. Therefore, the ranges of ventilation require careful analysis.

Heat Transfer to Environment

An animal can control, to some extent, the amount of heat transferred from its body by chemical and physical regulations. In a cold environment, the animal's metabolism increases, which increases the amount of heat production, offsetting heat transfer to the environment. (The principal result of such chemical regulation is inefficient feed utilization.) Physical regulation is also used in a cold environment; blood circulation to subcutaneous capillaries decreases, hair or feathers are erected, and animals huddle together in an attempt to reduce sensible heat loss. In a hot environment, opposite physical and physiological responses generally occur to enable transfer to the environment of heat associated with necessary and productive life processes. In addition, as sensible heat dissipation becomes more

difficult, evaporative heat loss increases and air moisture content becomes a factor in heat loss. Since the production of heat is a necessary by-product of growth and useful production, environmental limits to dissipating this heat cause a decrease in feed consumption and subsequent decrease in growth and production.

Most sensible heat of domestic animals is dissipated through the skin. Birds, sheep, and swine transfer most of their latent heat through the respiratory tract; cattle and horses transfer most of their latent heat through the skin. Blood transfers the heat produced by metabolism to the skin or to the lung surfaces, where it is dissipated by evaporation from the mucous layer coating the inside of the alveoli. Inspired air reaching the alveoli is heated almost to body temperature and may become nearly saturated with moisture. Expired air may not be saturated at body temperature—especially during periods of heat stress—because it is a combination of air, some of which has not reached deeply into the lungs. Minor amounts of heat are also transferred by ingestion of feed and water and through excretion.

Design factors affecting animal heat loss are (1) air temperature; (2) air vapor pressure; (3) air movement; (4) configuration, emissivity, absorptivity, and surface temperature of the surrounding shelter; and (5) temperature and conductivity of surfaces (e.g., floors with which the animal may be in contact).

Cyclic Conditions

The physiologic sensing elements respond both to environmental conditions and to changes in those conditions. Cycles of temperature, pressure, light, nutrients, parasites, magnetic fields, ionization, and other factors frequently occur with little engineering control.

Light is perhaps the earliest discovered and most important controlled environmental variable affecting reproductive processes (Farner 1961). However, the effects vary widely among animal species and age. Some animals grow and remain healthy with or without light (e.g., growing swine), while for others, lighting management is important. Studies have shown that (1) short photoperiods induce or accelerate estrus development in sheep; (2) day length affects semen production in sheep and horses (Farner 1961); (3) continuous white incandescent light during incubation caused White Leghorn eggs to hatch from 16 to 24 h earlier than eggs incubated in darkness (Shutze et al. 1962); and (4) red, yellow, or blue lights gave comparable results. Use of lights for only one of the three weeks also reduced the time required for hatching, but differences were not as marked. Percent hatchability was not affected by lighting treatments.

Light is used to delay sexual maturity in hens, which enhances subsequent production. This is done by gradually decreasing day length from hatching to 22 weeks of age or by abruptly decreasing day length to 9 h at 14 to 16 weeks of age. If pullets have previously been exposed to an increasing day length, the change should take place at 14 weeks of age; if exposed to a constant or decreasing schedule, a change at 16 weeks is adequate. Light intensities of 10 to 20 lx measured at bird height were adequate in all cases. Light can then be abruptly increased at 21 weeks of age to 14 or 16 h of light. The economic value of increasing day length beyond 14 h in a windowless poultry house, and 16 h in an open poultry house, has not been proved. Photoperiods such as 8 h of light (L), 10 h of darkness (D), 2 L and 4 D, and other cycles have improved feed utilization, egg production, and poultry growth (Buckland 1975, Riskowski et al. 1977).

Continuous light from hatching through 20 to 21 weeks of age markedly depressed subsequent egg production and caused a severe eye abnormality, but did not depress egg mass. (Light intensity was 10 to 30 lx, measured at bird height.)

Temperature cycles have been studied in cattle (Brody et al. 1955, Kibler and Brody 1956), swine (Bond et al. 1963, Nienaber et al. 1987), and poultry (Squibb 1959). The results differ somewhat among animals. Heat loss from cattle and swine can usually

be calculated from average daily environmental temperatures with sufficient accuracy for design load calculation.

Productivity is only slightly different for averaged temperatures when cyclic conditions with a range less than 10K are experienced (Squibb 1959). Above that range, productivity is depressed below that expected from the averaged temperature as determined in constant temperature tests, but under diurnally varying air conditions (15 to 25°C temperature and widely varying humidities), near-normal egg production is maintained.

Air Composition and Contaminants

The major contaminants in livestock housing are (1) respirable dusts from feed; manure; and animal skin, hair, and feathers; (2) microbes, both pathogenic and nonpathogenic, hosted in the respiratory tracts, animal wastes, or feed; and (3) several noxious gases of various concentrations. Respirable dust particles have diameters between approximately 0.5 and 5 μm . Gases are produced from the metabolic processes of animals, from the anaerobic microbial degradation of wastes, and from combustion processes. The gases of most concern are ammonia, hydrogen sulfide, carbon monoxide, and methane.

Dust levels in animal housing are high enough to create a nuisance in and near animal buildings, increase labor requirements for building and equipment maintenance, and interfere with the performance of heating and ventilating equipment. Dust has been implicated in poultry building fires. Dust is generated primarily by feed handling and increases with animal activity and air movement causing reentrainment of settled dust.

Contaminants are a concern because they predispose animals to disease and poorer performance and affect operator health. Animals experiencing stress (e.g., newborns, hot or cold, nutritionally limited, and sick animals) are more sensitive, and the presence of low levels of contaminants can have adverse effects on them.

Particulates (dust, endotoxins, live and dead microorganisms) and gases (ammonia, carbon dioxide, and hydrogen sulfide) in swine buildings (Zejda et al. 1993, Senthilselvan et al. 1997) have been implicated as contributors to the increased incidence of respiratory disorders among livestock producers compared to grain farmers and non-farm workers (Donham et al. 1989, Dosman et al. 1988). Young farmers may be at particular risk of developing chronic bronchitis, coughing, wheezing, toxic organic dust syndrome, and/or occupational chronic pulmonary disease (Zejda et al. 1994). For example, 33% of pork producers in Europe suffer chronic respiratory symptoms related to poor indoor air quality (Van't Klooster 1993). In the Netherlands, 10% of swine producers had to change jobs due to severe respiratory problems caused by poor air quality (Preller et al. 1992). In cold climates, the problems appear to be more serious because of (1) larger building size and longer working hours and (2) lower air exchange rates due to cold climates and energy conservation concerns.

Particle size is most commonly described using aerodynamic diameter, which is defined in terms of its aerodynamic behavior rather than its geometric properties. Aerodynamic diameter is a function of its equivalent geometric diameter, density, and a shape factor. The aerodynamic diameter of a particle is the diameter of a spherical water droplet having the same settling velocity as the particle of concern. Size distribution of dust particles influences the dust transportation and its effect on a human respiratory system. The human eye can only see a particle larger than 50 μm under normal light. For evaluating animal buildings, particle size is often divided into the following categories:

- Total dust = all sizes of particles suspended in the air
- Inhalable dust = all sizes of particles that are inhaled by a sampling instrument
- Respirable dust = particles smaller than 10 μm

In animal facilities, ultrafine particles ($< 0.5 \mu\text{m}$) are usually excluded from the evaluation because they are primarily background dust and not the concern of the indoor environment. If the dust concentration is measured in counts rather than mass, the ultrafine particles can dominate over the counts of the other particle sizes and cause large errors (Zhang et al. 1994).

Dust in animal buildings is different from other types of buildings in at least three aspects. First, animal building dust is biologically active in that it contains a variety of bacteria, microorganisms, and fungi (Martin et al. 1996, Wiegard and Hartung 1993). Second, its concentration is high, typically more than ten times higher than office buildings and residential buildings. Third, it is an odor carrier. Dust sources and flora are summarized in Table 1. Of those microbes, some are transmittable to people. For example, *Listeria monocytogenes* and *Streptococcus suis* are zoonotic agents that have caused fatal diseases in people (Fachlam and Carey 1985, Bortolussi et al. 1985).

Table 1 Dust Sources and Flora in Swine Buildings

Dust Sources	
Feed particles:	
	Grain dust
	Antibiotics
	Growth promoters
Swine protein:	
	Urine
	Dander
	Serum
Other agents:	
	Swine feces
	Mold
	Pollen
	Grain mites, insect parts
	Mineral ash
	Gram-negative bacteria
	Endotoxin
	Microbial proteases
	Ammonia adsorbed to particles
	Infectious agents
Microbial flora	
Gram-positive cocci:	
	<i>Staphylococcus</i> species (coagulase-negative)
	<i>Staphylococcus haemolyticus</i>
	<i>Staphylococcus hominis</i>
	<i>Staphylococcus simulans</i>
	<i>Staphylococcus sciuri</i>
	<i>Staphylococcus warneri</i>
	<i>Micrococcus</i> species
	<i>Aerococcus</i> species
	<i>Streptococcus equines</i>
	<i>Streptococcus suis</i> (presumptive)
	<i>Enterococcus durans</i>
Gram-positive bacilli:	
	<i>Corynebacterium</i> species
	<i>Corynebacterium xerosis</i>
	<i>Bacillus</i> species
Gram-negative bacilli:	
	<i>Acinetobacter calcoaceticus</i>
	Nonfermentative gram-negative bacillus:
	<i>Enterobacter calcoaceticus</i>
	<i>Pasteurella</i> species
	<i>Vibrio</i> species
Fungi:	
	<i>Alternaria</i> species
	<i>Cladosporium</i> species
	<i>Penicillium</i> species

Source: Zhang (1995, 1996).

Threshold limit values for different types of exposure are available (Table 2). These limit values are likely additive. For example, someone exposed to 75% of maximum ammonia level may be exposed to no more than 25% of the maximum for any other contaminant or combination of contaminants. Due to its biological nature, a lower limit for animal building dust may be warranted. For example, Donham et al. (1989) proposed a more stringent threshold TWA value of 0.23 mg/m³ respirable dust for farm animal buildings.

Airborne dust and microbes have been linked to respiratory disease in cattle, poultry, swine, horses, and laboratory animals. Infectious diseases, such as viral pneumonia and diarrhea, in calf barns have caused mortality rates between 20 and 80%, with the highest mortality occurring in enclosed barns that were underventilated during cold weather. Many respiratory diseases of poultry have been found to be transmitted via pathogenic microbes that can travel over 50 km and remain infectious for months (Siegmund 1979). Respiratory diseases are also costly to the swine industry—the incidence of enzootic pneumonia in pigs has ranged from 30 to 75%.

Gaseous ammonia is frequently a contaminant causing serious problems in swine and poultry housing. Ammonia levels of 50 ppm have been shown to reduce body mass gain rates of swine (Curtis 1983), and many researchers suspect that adverse health effects begin at levels below 25 mg/kg. Some physiologists and veterinary science researchers suggest that the level is between 5 and 10 mg/kg (Donham 1987). Ammonia at concentrations greater than 60 mg/kg has been implicated in reduced body mass and feed consumption, and in increased ocular and respiratory problems with broiler chickens (Carr and Nicholson 1980). Ammonia levels are influenced by animal diet, the ventilation rate, sanitation practices, and the waste-handling system. Ventilating for moisture control is usually adequate to control ammonia below 10 mg/kg in buildings sanitized monthly, where wastes are not allowed to accumulate for more than two weeks and where manure solids are covered by water.

Hydrogen sulfide is produced mainly from the wastes and is present at toxic levels that usually cause problems only when liquid wastes are agitated or pumped and emitted gases can filter into the animal occupied area. Hydrogen sulfide production can rise to lethal levels when manure in a pit below the animals is agitated, so extra precautions are necessary to ensure that ventilation is sufficient to remove the contamination.

Carbon monoxide is usually produced by malfunctioning fuel-burning heaters and internal combustion engines used for spray washing equipment. Many heaters are unventilated, which, when combined with the corrosive environment in livestock housing, makes this equipment susceptible to failure. Heaters should be vented to the outdoors or sensors should be installed to ensure complete combustion.

PRINCIPLES FOR AIR CONTAMINANT CONTROL

Reducing dust concentration by 85% or reducing dust inhalation by wearing a respirator improves human respiratory responses significantly (Senthilselvan et al. 1997, Zhang et al. 1998, Barber et al. 1999). Air contaminant control strategies include source suppression, air cleaning, and effective ventilation.

Source Suppression

Spreading (e.g., spraying, sprinkling, or fogging) a small quantity of oil, water, emulsifier or mixture of these can reduce dust concentration in the air (Takai et al. 1993, Zhang et al. 1995, 1996). Adding oil or fat to feed (Heber and Martin 1988) reduces emission of large feed dust particles. Other management practices, such as wet feeding, power washing, and maintaining sanitation in the facility also reduces the production and emission of air contaminants.

Table 2 Gas and Dust Threshold Values for People Exposure

Contaminant	Specific Density ^a	Odor	TWA ^b	STEV ^b	FEV ^c
Toxic gases (ppm in volume)					
Ammonia	0.6	sharp, pungent	25	35	300
Hydrogen sulfide	1.19	rotten eggs, nauseating	10	15	150
Methane	0.5	none	n/a	n/a	500 000
Carbon dioxide	1.53	none	5 000	30 000	50 000
Dust (mg/m³)					
Respirable			175	n/a	n/a

^aRelative to the density of air.

^bFrom American Conference of Governmental Industrial Hygienists (ACGIH 1998).

^cFrom Canada Plan Service, M-8710 (1985), M-9707 (1992).

n/a = currently not available

TWA = time-weighted average, for 40 hours per week

STEV = short-term exposure value for not exceeding 30 minutes

FEV = fatal exposure values

Air Cleaning

Generally, air contaminants can be removed mechanically, electrically, chemically, or biologically. **Mechanical air cleaning** includes filtration, scrubbing, and aerodynamic separation (cyclones or dust separators). Existing mechanical air cleaning methods, including fiber filters, require large quantities of airflow through the filtration media. For many dusty environments such as found in animal buildings, this type of cleaner requires frequent maintenance.

Cyclones use centrifugal force to separate particles from the main air stream. But a high pressure drop (typically higher than 500 Pa) across the cyclone is required to create the cyclone effect. This high pressure requires a large amount of power and creates high turbulence, which reduces the particle separation efficiency. Carpenter (1986) concluded that it is impractical to separate particles smaller than those that cause health concerns in animal buildings.

Electrical air cleaning includes ionization, electrostatic precipitation, and ozonation. The principle of the three technologies is to charge a dust particle with polarized electrical particles (ions or electrons) so that the charged dust particles can be attracted to a neutrally or opposite charged surface. Challenges of the ionization technology for livestock buildings include dust removal efficiency, initial and maintenance costs, and a potential problem of static electricity when used under cold and dry weather conditions.

The air cleaning efficiency of an electrostatic precipitator is proportional to the airflow rate through the precipitator. A large airflow rate in an airspace can reentrain a large amount of settled dust and thus create a high dust concentration in the air. Dust reduction efficiency, airflow rate, and power consumption of the air delivery through the precipitator must be balanced for optimum performance. Similar to air filters, an electrostatic precipitator requires frequent cleaning and maintenance. When dust particles accumulate on the precipitation surfaces of the device, the air cleaning efficiency rapidly decreases.

Ozone can effectively reduce airborne microorganisms in an animal building. Care must be taken to maintain an appropriate concentration because ozone is a potential irritant to humans and animals.

Ventilation Requirement

Ventilation is the primary method for controlling air quality in confinement buildings as it brings in fresh air to dilute the contaminants. The logic of ventilation is illustrated in Figure 5. Unlike residential or office buildings, the minimum ventilation for animal

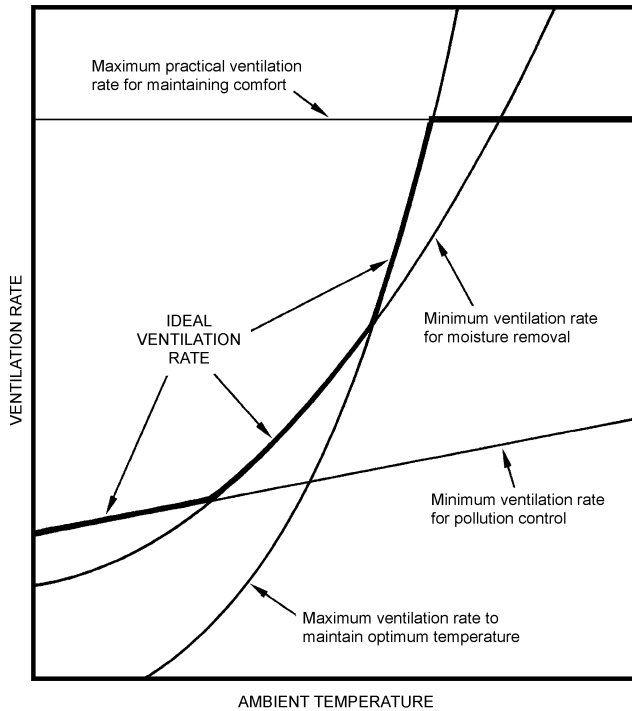


Fig. 5 Logic for Selecting the Appropriate Ventilation Rate in Livestock Buildings
(Christianson and Fehr 1983)

buildings is often determined by humidity or contaminant (such as ammonia) balances. Therefore, ventilation requirements must be calculated for sensible heat, humidity, and a given contaminant to determine the minimum ventilation for an animal building.

Volumetric ventilation requirement for sensible heat balance V_s , moisture balance V_w , and contaminant balance V_c (in m^3/s) can be calculated as follows:

$$V_s = \frac{q_n v}{(h_s - h_{so})} \quad (1)$$

$$V_w = \frac{W_n v}{(w - w_o)} \quad (2)$$

$$V_c = \frac{M_c v}{(c - c_o)} \quad (3)$$

where

- v = specific volume of air, m^3/kg
- q_n = net heat transfer rate through the building shelter, kW
- h_s = sensible heat content of room air, kJ/kg
- h_{so} = sensible heat content of outside air or supply air, kJ/kg
- w = moisture content of room air, kg/kg of air
- w_o = moisture content of outside air, kg/kg of air
- W_n = production rate of moisture within the room, kg/s
- c = contaminant concentration of room air, kg/kg of air
- c_o = contaminant concentration of outside or supply air, kg/kg of air
- M_c = production rate of the contaminant in the room, kg/s

Ventilation Effectiveness

Two terms are often used to evaluate a ventilation system: ventilation efficiency and ventilation effectiveness. **Ventilation efficiency** is a criterion for energy and fan performance; it is not directly related to ventilation effectiveness and air quality control.

Ventilation efficiency refers to the mass of air delivered per unit of power consumed by the ventilation system at a given pressure. The more air delivered per unit of power, the more efficient the ventilation system. It is also called the **ventilation efficiency ratio** (VER) or **energy efficiency ratio** (EER) (Pratt 1983).

Zhang et al. (2000) proposed a **ventilation effectiveness factor** (VEF) to quantitatively describe the ventilation effectiveness for controlling indoor air quality. The VEF can be defined as the ratio of two contaminant concentration differentials:

$$\text{VEF} = \frac{C_x - C_s}{C_m - C_s} \quad (C_m > C_s \text{ and } C_x > C_s) \quad (4)$$

where C_x is the contaminant concentration under complete mixing conditions, which can be determined based on the mass balance of the contaminant of concern. For a ventilated airspace at steady state, the amount of contaminant removed by the exhaust air must equal the sum of the amount of contaminant brought in by the supply air plus the contaminant produced in the airspace, regardless of complete or incomplete mixing conditions. The contaminant concentration of the exhaust air C_e can be measured. Under complete mixing conditions, C_e is the same as the C_x ; thus,

$$C_x = C_e \quad (5)$$

C_s is the contaminant concentration of the supply air, C_m is the mean contaminant concentration of the airspace at n measured locations.

$$C_m = \frac{1}{N} \sum_{i=1}^N C_i \quad (6)$$

Substituting Equations (5) and (6) into Equation (4), ventilation effectiveness factor becomes

$$\text{VEF} = \frac{N(C_e - C_s)}{\sum_{i=1}^N C_i - NC_s} \quad (C_e > C_s) \quad (7)$$

The ventilation effectiveness factor is nondimensional and independent of the ventilation rate. The higher the value of the factor, the more effective the ventilation system for contaminant removal. When $C_e < C_s$, the airspace becomes a settling chamber or an air cleaner and the air cleaning efficiency $\xi = 1 - C_e/C_s$ should be used to evaluate the system. When the contaminant concentration of supply air is negligible, i.e., $C_s \approx 0$, the ventilation effectiveness factor becomes

$$\text{VEF} = \frac{C_e}{C_m} \quad (8)$$

One useful feature of VEF is that the system being evaluated can be its own control. This feature is particularly valuable for evaluating or troubleshooting in the field. From Equation (4) and Equation (8), the VEF compares the actual contaminant concentration with its own concentration under complete mixing conditions in the same airspace. The existing methods of evaluating ventilation effectiveness often require comparing two systems. In practice, it is usually difficult to find an identical system for comparison.

A ventilation effectiveness map (VEM) such as shown in Figure 6 is a useful tool for design, analysis, and modification of a ventilation system. It is a contour plot of the ventilation effectiveness factors calculated using Equation (8) for the entire airspace. Dust mass was measured concurrently at several locations throughout the building cross section and the VEF values were calculated from that

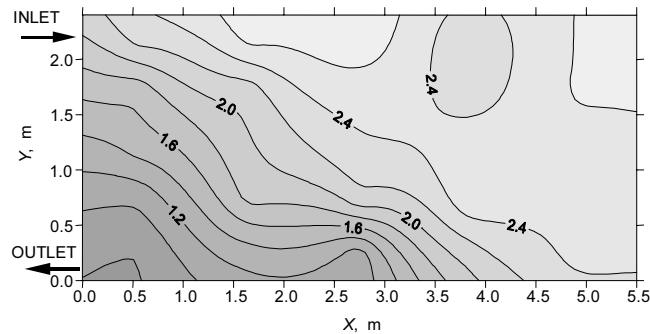


Fig. 6 Typical Ventilation Effectiveness Map for a Room
(Room is 5.5 m long by 3.7 m wide by 2.4 m high with slot air inlet at top of one wall and air outlet near bottom of same wall.)

data. The higher the VEF values in the map, the more effective the ventilation system is in that area.

Improved ventilation effectiveness is an important strategy to reduce contaminant concentration in animal buildings. It is very expensive to clean large quantities of air and it is difficult to move the air through central cleaning equipment without creating drafts. Incomplete mixing ventilation such as **displacement** and **zonal ventilation** has great potential in creating a cleaner zone in a dusty airspace without changing the overall ventilation rates.

Interactive Stressors

Thermal (air temperature, air humidity, air velocity, and surrounding surface temperatures) and air quality (relative absence of dust, microbes, and contaminant gases) are the two stressors of most concern to ventilating a livestock structure. However, health status, animal age, stage of production, nutrition, and social conditions interact with the thermal and air quality conditions to determine animal health and performance.

Whether stressors are linearly additive or otherwise is an important research area. McFarlane (1987) found that ammonia, heat, acoustic noise, disease, and beak-trimming stressor effects on chickens were linearly additive in effect on the feed efficiencies and daily gain rates.

Comparing Individual Animal and Room Heat Production Data

Liquid wastes from urine, manure, waterer spillage, and cleaning affect the sensible and latent heat fraction in a room (ASAE 1991). More water on the floors requires more thermal energy from the animals or the building heating system to evaporate the moisture. This evaporated moisture must then be removed by ventilation to prevent condensation on building surfaces and equipment and minimize adverse health effects, which can occur when humidities exceed 80%.

Floor flushing or excessive water spillage by animals can increase latent heat production by one-third from animal moisture production data, with a corresponding reduction in sensible heat production on a per-animal basis (ASAE 1991). Partially slatted floors with underfloor storage of wastes reduce the room moisture production by approximately 35%, compared to solid floor systems. Rooms with slatted floors throughout the building may have moisture production rates as much as 50% lower than solid floors. Therefore, slatted floors reduce the ventilation rate required for moisture removal, while excessive water spillage increases the moisture removal ventilation rate.

Influence of Genetic Change and Breed on Heat Production

Researchers have noted significant genetic correlations with performance. For example, swine breeds with high fat content characteristics outgained low fat content breeds, but the low fat content lines used feed more efficiently (Bereskin et al. 1975). Barrows (male hogs castrated before sexual maturity) ate 6% more than gilts (young sows that have not farrowed) to sustain a 7% faster growth rate.

Genetic improvements within breeds suggest that performance data should be updated periodically. Between 1962 and 1977, for example, the average gain rate for swine increased 70 g per day, and feed efficiency improved 15% for Missouri hogs (Thomeczek et al. 1977).

CATTLE

Growth

Figure 7 shows the general growth rate for both beef and dairy breeds. Efficiency of beef calf growth is of economic importance; the dairy calf is developed for adult productive and reproductive capacity. Fattening calves and yearlings could be fed increasing amounts of grain and hay, with an expected gain of about 0.9 kg per day. Figure 8 shows the effect of temperature on the growth rate of several breeds of beef calves.

Food and energy requirements for growth can be computed by taking the difference between the energy in the available ration consumed and the energy required for maintenance and growth. Energy requirements for maintenance at an air temperature of 20°C has been reported to be 9.13 kJ/h per kilogram of body mass (Blaxter and Wood 1951), 8.42 kJ/h (Bryant et al. 1967), and 8.80 kJ/h (Gebremedhin et al. 1983). Using 3413 kJ/kg body tissue for conversion of feed energy to body tissue (Brody 1945), the growth rate of a calf at 21°C (0.54 g/h gain per kilogram of body mass) can be nearly 30 times that of a calf being kept at 3°C [18 mg/(h·kg)]. Alternatively, to get the same growth rate at 3°C as at 21°C, the same ration must be fed at the rate of 11.6% of body mass each day, a 16% increase (Gebremedhin et al. 1981).

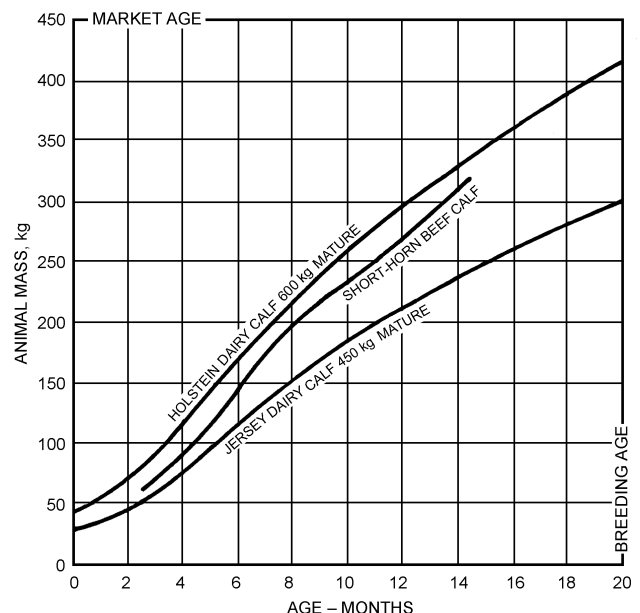


Fig. 7 General Growth Curves for Calves Fed Grain
(Johnson et al. 1958, Ragsdale 1960)

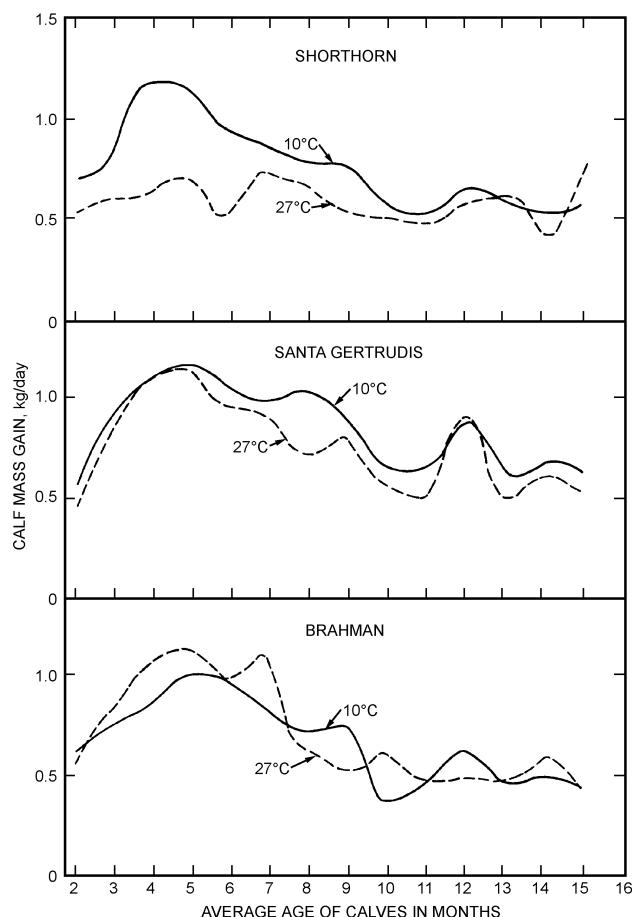


Fig. 8 Daily Mass Gain of Beef Calves
(Longhouse et al. 1960)

Lactation

Figure 9 illustrates the effect of high temperature on the milk production of one Holstein in a test designed to study the combined effects of temperature and humidity. The dotted line represents the normal decline in milk production (persistence) from an advancing stage of lactation.

The ideal environment for Holstein cattle should not exceed 24°C. Jerseys are somewhat more heat tolerant, and their limit can be 27°C (Yeck and Stewart 1959). At the lower end of the temperature scale, production decreases may be expected at -1°C for Jerseys and below -12°C for Holsteins and Brown Swiss.

A temperature-humidity index (THI) expresses the relationship of temperature and humidity to milk production. Temperature-humidity indexes have a greater effect on cows with a genetic potential for high milk production than for those with a lower potential (Figure 10).

Under high temperatures, a cooling system can help maintain milk production and reproductive function. In field studies conducted by Bucklin and Turner (1991) in both warm and hot, humid climates, a system providing evaporative cooling by forced air movement and direct sprinkling of lactating cows increased milk production by a range of 7 to 15% over cows not exposed to cooling.

Reproduction

Prolonged low temperatures, even those well below freezing, do not affect the reproductive performance of farm livestock, but breeding efficiency of both sexes decreases under summer conditions. Sustained temperatures above 30°C may decrease fertility,

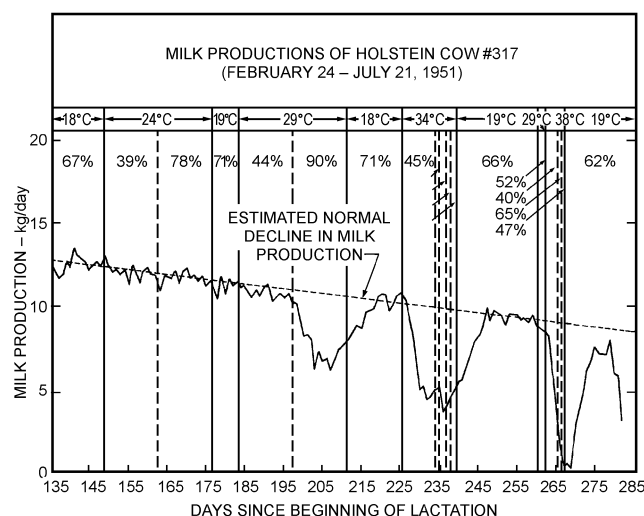


Fig. 9 Milk Production Decline of One Holstein During Temperature-Humidity Test
(Yeck and Stewart 1959)

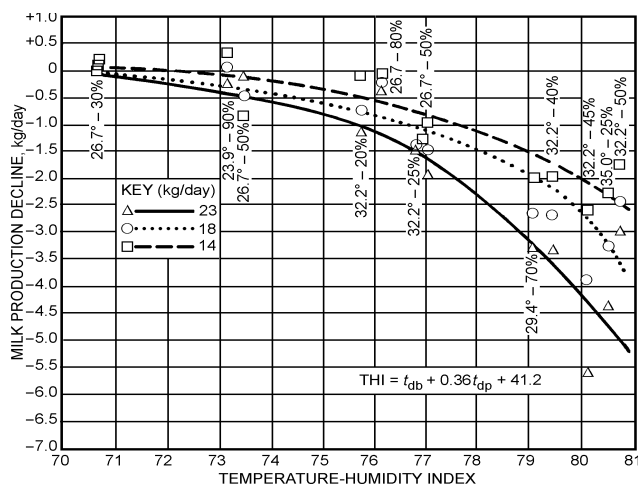


Fig. 10 Effect of Milk Production Level on Average Decline in Milk Production Versus Temperature-Humidity Index
(Johnson et al. 1962)

sperm production, and semen quality of males, and increase anestrus and embryonic death in females. In bulls, temperatures above 24°C decrease spermatogenesis, and long exposures at 30°C or above cause temporary sterility. The extent of the reaction depends on temperature rise and exposure duration.

In females, Guazdauskas (1985) observed that conception rates decreased from a range of 40 to 80% conception in thermoneutral environments (10 to 22°C) to a range of 10 to 51% conception in hot environments (>27.5°C). A cooling system involving a cooled shade and artificially induced air movement increased breeding efficiency by approximately 100% in a hot climate (Wiersma and Stott 1969).

Heat and Moisture Production

Sensible and latent heat production from individual animals (Figure 11) differ from the stable heat and moisture production of animals (Figures 12 and 13). The data in Figures 12 and 13 were obtained while ambient conditions were at constant temperatures

and relative humidities were between 55 and 70%. The effects of evaporation from feces and urine are included in these data.

The rate of cutaneous water loss is very small at colder temperatures but rises sharply above 18°C. Cutaneous evaporation as a means of heat loss in calves becomes increasingly important as the air temperature rises above 24°C. As the air temperature rises, the proportion of nonevaporative cooling decreases. Above 30°C, about 80% of the heat transferred is by evaporative cooling. Gebremedhin et al. (1981) observed that cutaneous water loss from calves varied between 0.06 and 0.4 g/h per kilogram of body mass for air temperatures between 0 and 18°C and increases steadily beyond 18°C (Figure 14). Water loss by respiration, the other avenue of loss, is shown in Figure 15.

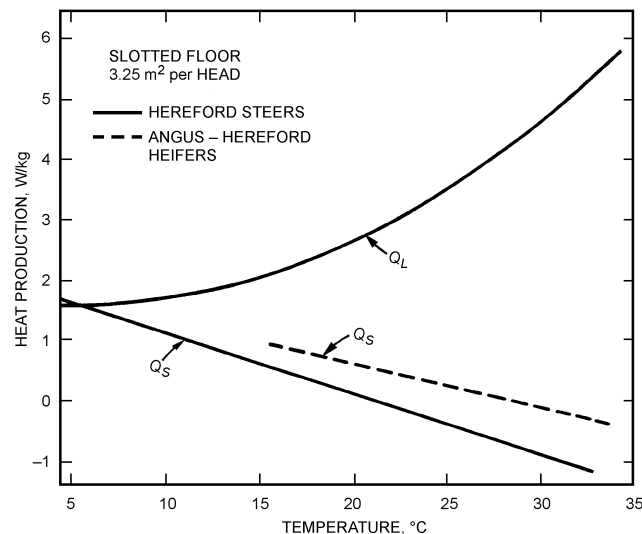


Fig. 11 Sensible and Latent Heat Production per Unit Livestock Mass (Hellickson et al. 1974)

SHEEP

Growth

In normal environments, an average daily gain of 0.25 kg per day can be expected of lambs marketed at 40 to 60 kg, depending on breed. Hampshires often gain more than 0.5 kg per day, and lambs can be fed to have a mass over 90 kg while still under a year old.

Variations exist among breeds and strains of sheep in their ability to adjust to environmental changes. Temperature effects on sheep growth suggest a lower rate at elevated temperatures. A South African study shows that lack of shade in warm climates reduces growth rate. Australian studies indicate that Merino lambs survive for only about 2 h in an air temperature of 38°C.

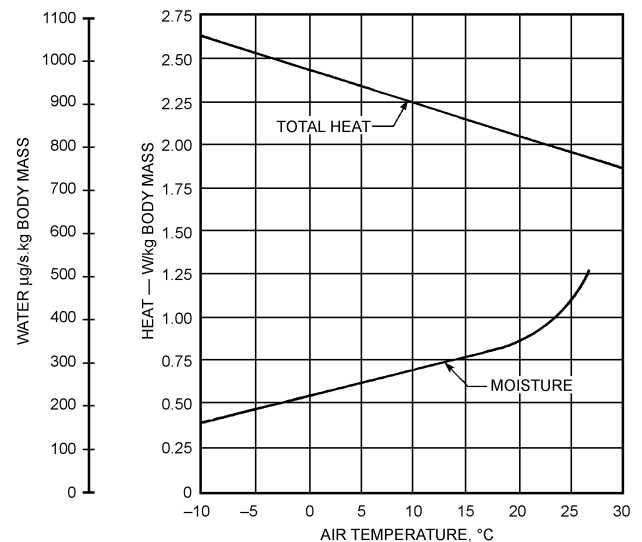


Fig. 12 Stable Heat and Moisture Dissipation Rates Dairy Cattle Stanchioned in Enclosed Stables (Yeck and Stewart 1959)

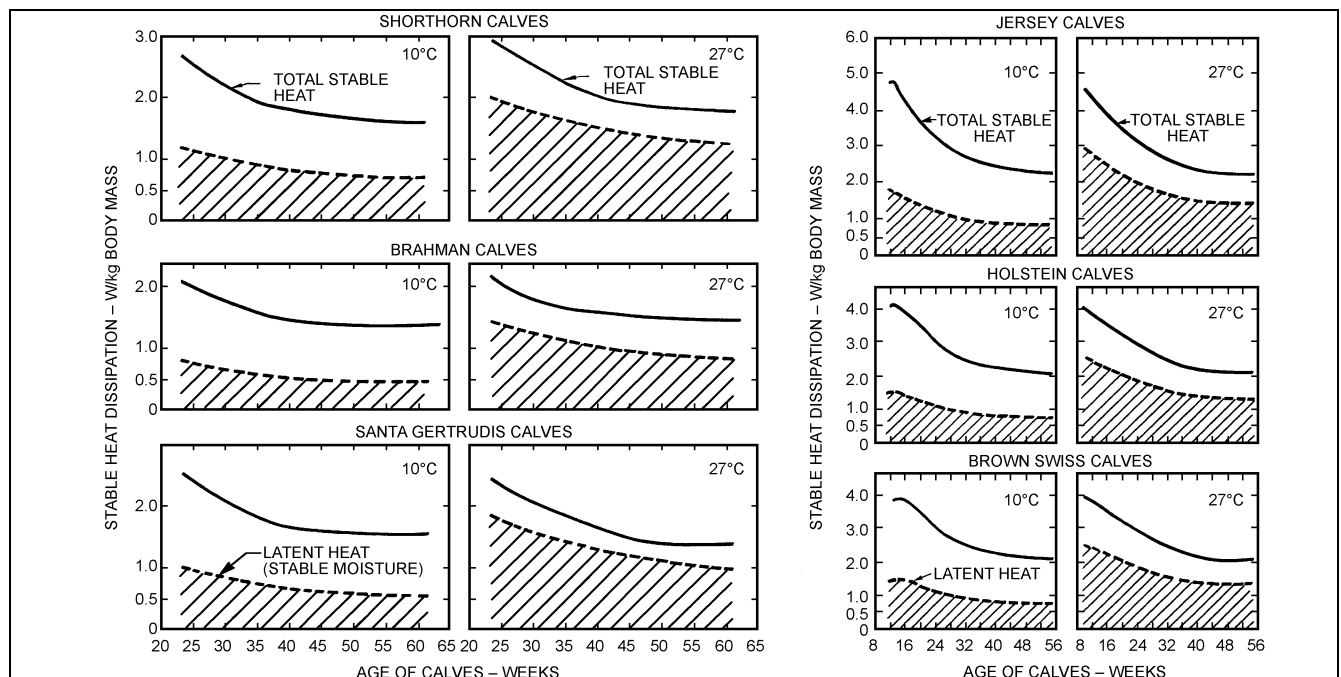


Fig. 13 Stable Heat and Moisture Loads for Beef and Dairy Calves in Pens (Yeck 1957, Yeck and Stewart 1960)

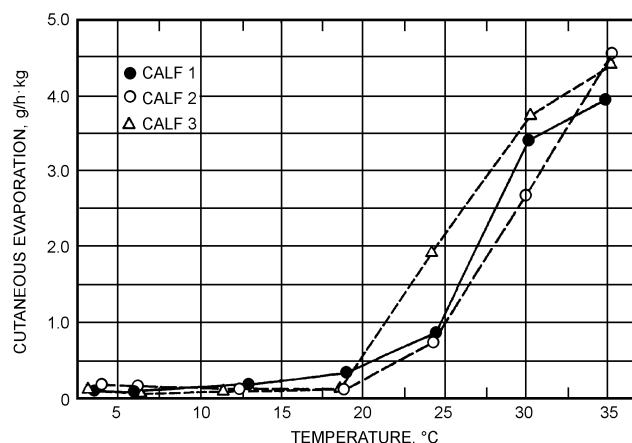


Fig. 14 Cutaneous Water Loss per Unit Body Mass of Holstein Calves
(Gebremedhin et al. 1981)

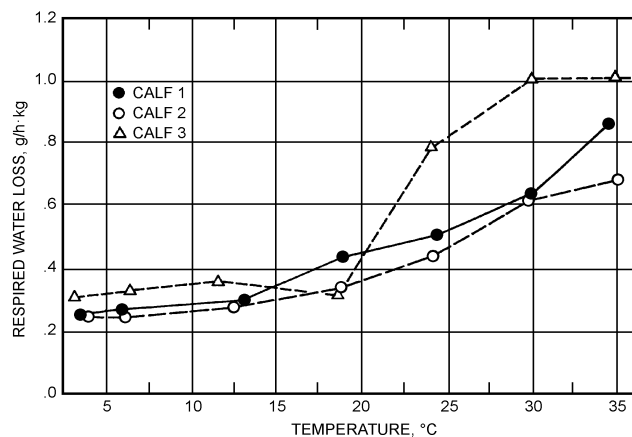


Fig. 15 Respiratory Water Loss per Unit Body Mass of Holstein Calves
(Gebremedhin et al. 1981)

Wool Production

The amount and quality of wool produced varies considerably among breeds, ranging from about 1.4 kg of poor quality wool from Dorset ewes (a breed developed primarily for mutton) to well over 4.5 kg of high quality fleece from dual-purpose breeds. Rambouillet, Merino, and Columbia-Southdale breeds supplied 3.2 kg per year, and about 2.0 kg was grown by a Hampshire, where monthly shearing increased wool production by about 0.5 kg per year.

Environmental factors such as photoperiod, nutritional level, and temperature also affect wool growth. Skin temperature is considered a dominant factor; high wool growth is associated with high skin temperatures. In a related study, low subcutaneous blood circulation limited wool growth. A thick fleece appears to limit radiant heat loads.

Reproduction

Sheep mate only during certain periods of the year, but they can sometimes be induced to mate outside the normal season if the natural environment is modified. Ewes may breed if exposed to an air temperature of 7°C before mating is attempted.

In studies on the effects of high temperatures on sheep reproduction, air temperature was reported to affect the spermatogenesis rate. Rams kept at 32°C environmental temperature showed a reduced

Table 3 Heat Production of Sheep

Fleece Length, mm	At 8°C		At 20°C		At 32°C	
	Total ^a	Latent ^b	Total ^a	Latent ^b	Total ^a	Latent ^b
Mature, maintenance-fed						
Shorn	2.6	8%	1.7	12%	1.3	38%
30	1.4	29%	1.3	28%	1.3	65%
60	1.3	23%	1.2	43%	1.2	76%
Lambs, 1 to 14 days						
Normal	6.7	—	5.0	—	—	—

Source: Scott et al. (1983).

^aW/kg of body mass

^bPercent of total heat

rate of spermatogenesis, although a 3-week period at 21°C effected recovery to the normal rate. Later reports suggest that high air temperatures may cause lowered fertility for other reasons. Subjecting ewes to 38°C just before mating causes fertilization failure because of some form of ovum structure degeneration.

Under practical conditions, early embryonic death appears to be the greatest loss in potential offspring conceived in a high-temperature environment. Degree of susceptibility to high temperature is greatest near mating time but generally decreases as the length of time after mating increases. A temperature of 32°C and 65% rh at mating kills most embryos at an early age. The same conditions applied later in gestation do not cause death, but do cause the birth of small, weak lambs. The longer the high-temperature period, especially during the last third of gestation, the greater the number of weak lambs born. All reproductive processes appear to be more adversely affected by high air temperature when accompanied by high relative humidity.

Heat Production

Only a few heat-production tests have been conducted, mostly for correlation with other physiological data. A lamb's ability to generate heat is important because it is normally born during the most severe climatic season. One study indicated newborn lambs were limited in heat production to 19.4 W/kg—five times the basal level. Test conditions were from -10 to 0°C with a 19 km/h wind, but lambs are capable of withstanding temperatures as low as -40°C. Table 3 provides heat production data for sheep; while the total heat production data are reliable, the latent heat proportions do not reflect the portions of sensible heat used for water and urine evaporation from flooring and bedding.

SWINE

Growth

Ambient air temperature affects the feed conversion and daily mass of growing swine. As shown in Figure 1B, a temperature range of 16 to 21°C produces maximum rates of gain and feed use for 70 to 100 kg hogs, while a broader range of 10 to 24°C reduces performance only slightly. For 20 to 59 kg animals, the optimal and nominal loss ranges are about 17 to 23°C and 13 to 24°C, respectively (Kibler and Brody 1956). Younger animals require temperatures of 23 to 28°C for best performance, and piglets from 3 days to 2 weeks of age should have 30 to 32°C conditions (Hahn 1983).

Daily air temperature cycles of more than 5 K on either side of 21°C result in reduced daily gain by pigs and an increased feed requirement per unit of gain (Nienaber et al. 1987). Reasonably constant air temperatures are desirable.

The level of air temperature in which swine grow affects deposition and retention of protein (carcass quality). Lean meat formation is reportedly highest in pigs raised between 16 and 21°C (Mount 1963). However, the ratio of protein to fat decreases at air temperatures above 16°C.

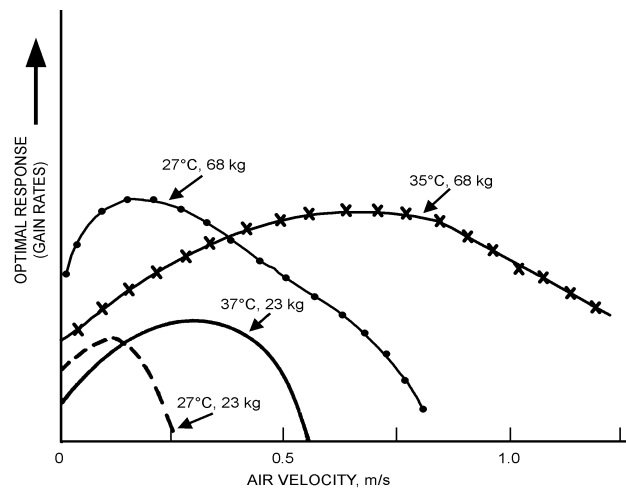


Fig. 16 Swine Response to Air Velocity
(Riskowski and Bundy 1986, Bond et al. 1965)

Table 4 Heat Production of Grouped Nursery Pigs

Weight Range, kg	Temperature, °C	Total Heat Production, W/kg	Latent Heat, % of Total
4 to 6	29	5.1	33
6 to 11	24	7.0	31
11 to 17	18	7.8	30

Source: Ota et al. (1982).

Swine gains and feed conversion rates are highly sensitive to air velocities and, in many cases, are affected adversely at velocities as low as 0.25 m/s. Swine less than 8 weeks of age should not be exposed to velocities greater than 0.25 m/s; a velocity lower than 0.13 m/s is preferred when temperatures are in the recommended range. Even in hot conditions, pigs are affected adversely by air velocities greater than 1 m/s (Bond et al. 1965, Gunnarson et al. 1967, Riskowski and Bundy 1991). Feed utilization and gain are much better at low air velocities (0.18 m/s) than at high (1.5 m/s) air velocities when temperatures are optimal (Figure 16).

Reproduction

Merkle and Hazen (1967) and Heard et al. (1986) have shown that sows benefit from some type of cooling in hot weather. In these studies, cool, dry air was directed at the sow to relieve heat stress by increasing evaporative and convective heat dissipation. Field studies of breeding problems and resultant small litters have established that both sexes suffer losses from high temperature. Sprinkling the sow during hot weather at breeding time and shortly after resulted in more live births than with unsprinkled sows. Sprinkling boars before mating also increased the number of live births per litter. Conception rate varied from about 100% of normal at 21°C to only 70% at 32°C. Breeding difficulties and a decrease in live embryos were observed in tests with controlled temperatures and relative humidities (Roller and Teague 1966). In some species, spontaneous abortion under severe heat stress may save the mother's life; however, sows appear to die of heat prostration, due to extra metabolic heat generation in late pregnancy, before spontaneous abortion occurs.

Little information is available on the value of temperature control for sows during cold weather. Forcing sows to produce the necessary heat to maintain body temperature may require rigid nutritional management to avoid the animals from becoming overweight—a condition resulting in poorer conception and smaller litters.

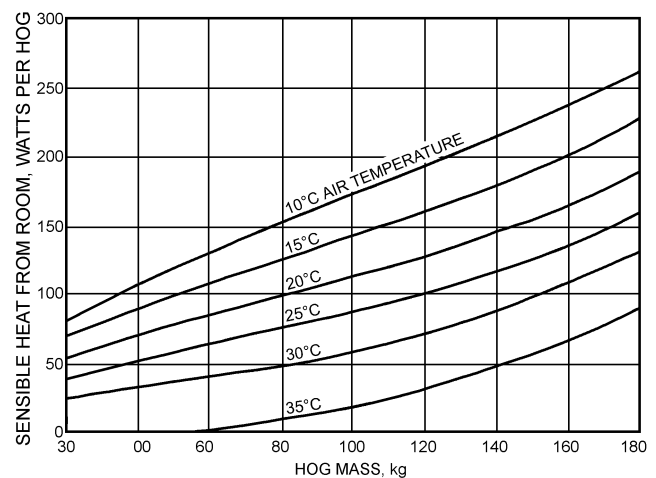


Fig. 17 Room Sensible Heat in Hog House
(Bond et al. 1959)

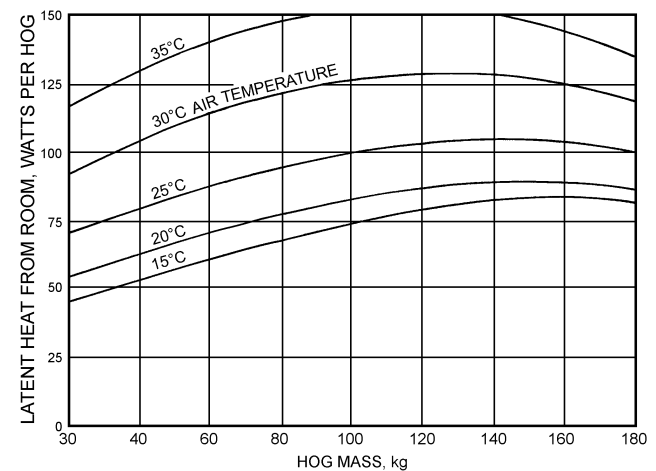


Fig. 18 Room Latent Heat in Hog House
(Bond et al. 1959)

Heat and Moisture Production

Table 4 (Butchbaker and Shanklin 1964, Ota et al. 1982) shows heat production for piglets. Figure 17 and Figure 18 (Bond et al. 1959) show heat and moisture that must be accounted for in ventilating or air conditioning older swine housing for swine between 20 and 180 kg, housed at temperatures from 10 to 32°C. These data are the sensible and latent heat levels measured in a room containing hogs. For design purposes, the room heat data reflect swine housing conditions rather than metabolic heat production from an individual animal.

The same data can be applied even where building temperatures are cycling, if the average air temperature during the cycle is used for design. The total animal heat load and the latent load that the ventilation system must remove are greater than the values in Figure 17 and Figure 18, if the air velocity around the animals is more than about 0.25 m/s.

The lower critical temperature (the ambient temperature below which heat production increases) is about 25 to 30°C for a group of newborn pigs; for a single piglet, the critical temperature is about 34 to 35°C. As the pigs grow, the critical temperature falls—for 2 to 4 kg pigs, it is between 30 and 35°C; for 4 to 8 kg pigs, between 25 and 30°C. The floor bedding materials for growing piglets influence these critical temperatures. For a group of nine pigs averaging 40 kg, the critical temperature is 12 to 13°C on

straw, 14 to 15°C on asphalt, and 19 to 20°C on concrete slabs (Butchbaker and Shanklin 1964).

CHICKENS

Growth

The tremendous worldwide production of broiler chickens is a result of improvements in genetics, nutrition, and housing. Two-kilogram broilers are produced in less than 6 weeks. Intermittent light and darkness (photoperiod) improve growth and conserve feed and energy (McDaniel and Brewer 1975).

Supplemental heat is generally needed for newly hatched chicks. Broiler strains respond well to brooding temperatures of 33°C for the first few days. Thereafter, air temperatures may be decreased at a rate of 4 K per week until 21°C is reached. Relative humidities of 65 to 70% promote good feathering and market-quality broilers. Effects of air velocity on heat dissipation of broilers is widely acknowledged, although not completely quantified, and has led to the widespread adoption of tunnel ventilation in new housing. Some benefit from increased velocity (up to 2.5 m/s) is obtained at air temperatures from 24 to 35°C (Drury 1966). High-velocity air, at a temperature above the feather temperatures, causes more, not less, heat stress. Observations showed that 28-day-old broilers rested in areas with airflow temperature combinations of 0.28 m/s at 15°C, 0.5 m/s at 21°C, and 0.75 m/s at 24°C.

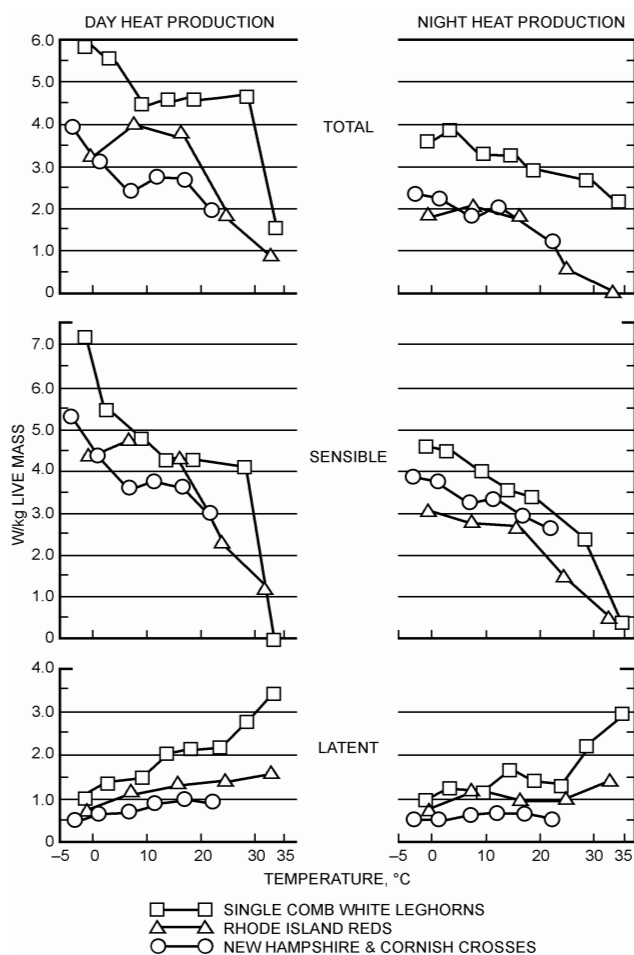


Fig. 19 Heat and Moisture Loads for Caged Laying Hens at Various Air Temperatures
(Ota and McNally 1961)

Reproduction

Adverse effects of high thermal environments (above 29°C) on egg production include fewer eggs, reduced egg mass, and thinner shells. Hens over 1 year of age are more adversely affected by high thermal environments than younger hens. Larger hens are more adversely affected than smaller hens. Hatchability also declines as temperatures increase. Although the fertility rate is good at 21°C, it declines at 30°C. Feed requirements increase markedly below 7°C; activity and productivity decline below 0°C. The suggested ideal environment is between 13 and 24°C.

Increasing relative humidity above 80%, at 29°C dry-bulb temperature, produces an increased respiration rate and drooping wings. After 7 to 10 days, acclimatization may reduce the respiration rate, but production will still be less than optimal. Generally, relative humidity can vary from around 40% to 75% with little impact on bird performance. Lower relative humidities may be associated with dusty conditions and signal excessive minimum ventilation; higher relative humidities are conducive to mold growth and building deterioration from excess moisture.

Heat and Moisture Production

Figure 19 shows the total sensible and latent heat produced by laying hens during day and night at various temperatures. Figure 20

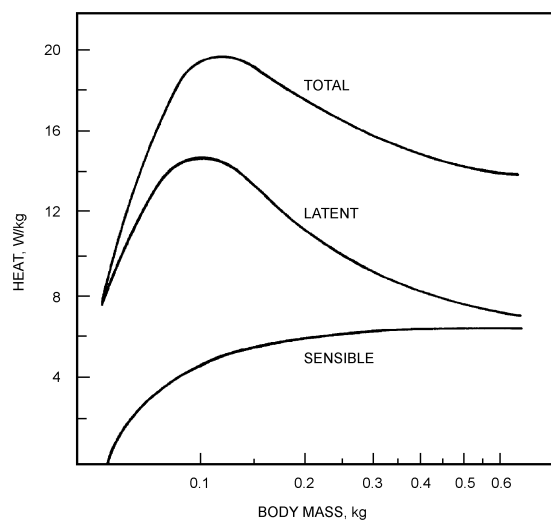


Fig. 20 Sensible, Latent, and Total Heat for Chicks Brooded on Litter
(Reece and Lott 1982)

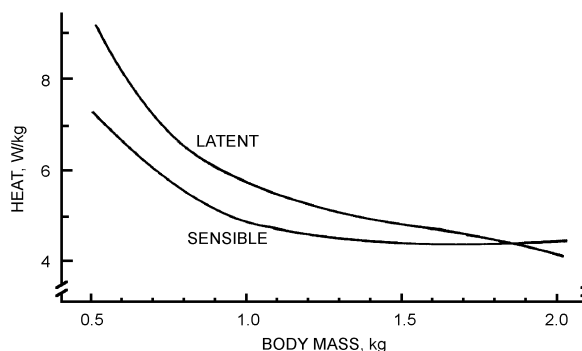


Fig. 21 Sensible and Latent Heat for Broilers Raised at 27°C on Litter
(Reece and Lott 1982)

shows the same data for chicks. [Figure 21](#) and [Figure 22](#) show sensible and latent heat production for broilers grown on litter at typical stocking rates at two temperatures. The effects of heat and moisture absorption or release by the litter are included in these figures. (Note: modern bird growth rates have increased approximately threefold since the work reported in [Figures 20, 21](#), and [22](#) was performed.)

The continued improvement in nutrition, genetics, and housing for poultry means that currently available data for heat and moisture production is outdated. Research by Gates et al. (1996) suggests that total specific heat production (i.e., expressed per kilogram of body mass) may be reasonably similar, but that partitioning between sensible and latent components has changed. In general, latent loads have increased during brooding and decreased during growout, presumably because of new water delivery systems with fewer leaks.

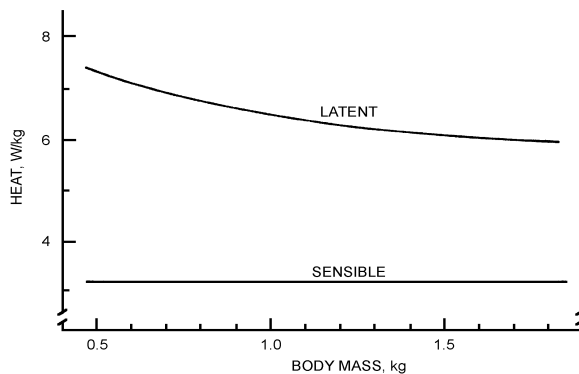


Fig. 22 Sensible and Latent Heat for Broilers Raised at 27°C on Litter
(Reece and Lott 1982)

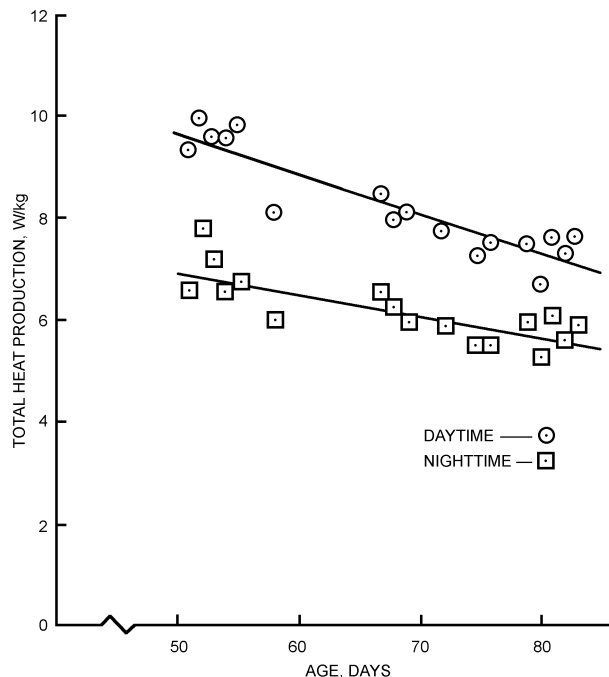


Fig. 23 Total Heat Production of Medium Breed Turkeys Versus Age During Daytime and Nighttime
(Buffington et al. 1974)

TURKEYS

Growth

The turkey poult has the best rate and efficiency of gain at a brooder room temperature of 21 to 24°C for the first 2 weeks, and 18°C thereafter, with about 70% rh. Initial brooder temperature should be 38°C, reduced 3 K per week until room temperature is reached. Proper control of photoperiod stimulates the growth rate in turkeys. [Table 5](#) shows weekly cumulative average live mass for both sexes (Sell 1990). [Figure 23](#) provides heat production data for medium breed turkeys.

Reproduction

Mature turkeys tolerate temperature and humidity over a range of at least -7 to 32°C and 35 to 85% rh. Since mature birds are kept only for fertile egg production, lighting for off-season egg production becomes very important. The young stock are raised to 20 weeks on natural light. At 20 weeks, females are placed in a

Table 5 Weekly Average Live Mass of Male and Female Turkeys

Age, Weeks	Male, kg	Female, kg
0	0.03	0.03
1	0.15	0.14
2	0.30	0.29
3	0.52	0.50
4	0.84	0.80
5	1.27	1.17
6	1.78	1.61
7	2.39	2.11
8	3.06	2.67
9	3.78	3.26
10	4.58	3.88
11	5.42	4.52
12	6.35	5.17
13	7.29	5.81
14	8.28	6.43
15	9.28	7.04
16	10.28	7.62
17	11.28	8.16
18	12.27	8.68
19	13.26	9.16
20	14.24	9.60
21	15.20	
22	16.12	
23	17.01	
24	17.88	

Source: Sell (1990).

Table 6 Heat Loss of Growing Turkeys at Various Air Temperatures and Relative Humidities

Age, Days	Mass of Poultry, kg	Dry Bulb, °C	Relative Humidity, %	Heat Loss, W/kg		Total Live Mass, kg
				Sensible	Latent	
15	0.221	38	23	1.48	10.64	12.12
6	0.106	35	26	4.97	11.74	16.71
19	0.364	35	26	2.13	6.51	8.64
14	0.235	32	31	5.93	7.03	12.96
29	0.740	32	31	3.61	3.93	7.54
7	0.111	29	36	7.87	9.09	16.96
21	0.419	29	36	4.97	5.16	10.13
36	0.908	29	36	4.39	2.77	7.16
28	0.629	27	42	5.81	2.64	8.45
23	0.437	24	50	6.97	4.00	10.97
27	0.568	24	50	7.55	2.00	9.55
35	0.962	24	50	6.13	1.68	7.81

Source: DeShazer et al. (1974).

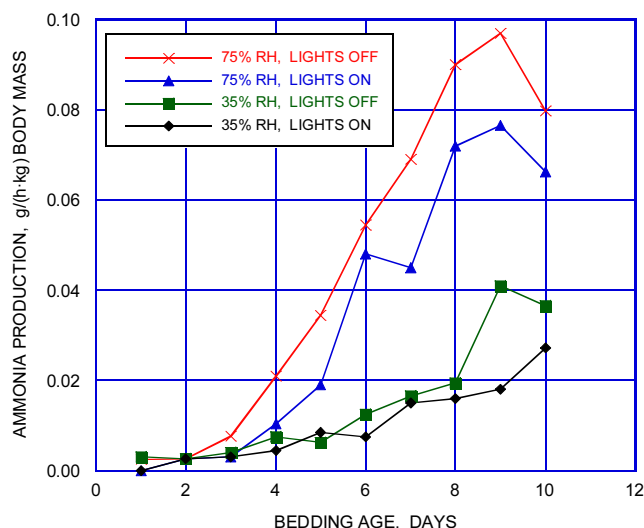


Fig. 24 Ammonia Generated by Laborator Mice

totally darkened pen and given 8 h per day illumination at an intensity of 20 to 50 lux at bird's-eye level. At 30 weeks, the sexes are mixed, and the lighting period is increased to 13 to 15 h. The breeding season then continues for 12 to 26 weeks.

Heat and Moisture Production

Table 6 gives limited heat loss data on large breed growing turkeys (DeShazer et al. 1974); however, an estimate from data on heavy chickens, applied to turkeys on a live-mass basis, should be satisfactory for design purposes. The reduction in heat loss during the dark period of the day is 25% for large breeds (Buffington et al. 1974) and between 5 and 40% for small breeds.

The latent heat production of turkeys may be significantly higher than the 1970s data show if the growth rate or feed consumption is significantly higher in the 1990s than it was in the 1970s (see the section on Chickens, Heat and Moisture Production).

LABORATORY ANIMALS

Significant environmental conditions for facilities that house laboratory animals include temperature, humidity, air motion, illumination, noise, and gaseous and viable particulate contaminants (Moreland 1975). Design conditions vary widely, depending on whether the animals are experiencing disease-induced stress (which alters environmental needs), subjected to test environments, or simply housed (Besch 1975, Murakami 1971, Nienaber and Hahn 1983). This fact reflects differing housing and ventilation guidelines for animals used in research (NIH 1985), compared to recommendations by the ASAE (1991) and Midwest Plan Service (MWPS 1983) for production agriculture. Little is known about the influence of disease on environmental requirements, animal performance, and well-being. Because significantly different conditions may exist between animal cages and the animal room (macroenvironment), control of cage environments is essential to ensure the animal's physiological well-being. Temperature and velocity gradient controls require low supply air-to-room air temperature differential, overhead high induction diffusion, uniform horizontal and vertical air distribution, and low return outlets.

Heat and Moisture Production

Memarazadeh (1998) reported CO₂, H₂O and NH₃ generation rates, O₂ consumption rates, and heat generation rates of laboratory mice. The rates were measured at two room relative

Table 7 Average Production/Consumption Rates for Laboratory Mice

Production/Consumption Rates per Kilogram of Body Mass	Light Period	Dark Period	Light/Dark Average
Total heat, W	23	27	—
Water generated, kg/h	—	—	0.08
CO ₂ generated, kg/h	0.0068	0.0090	—
O ₂ consumed, kg/h	0.0059	0.0066	—

Notes:

1. Mice were white laboratory females in shoebox cages with chipped hardwood bedding.
2. Heat production rates were calculated from O₂ consumption data. A mixed respiratory quotient (RQ) was assumed (RQ = 0.82), and heat production was based on a rate of 0.020 kJ/m³ of O₂ consumed.

Table 8 Heat Generated by Laboratory Animals

Animal	Mass, kg	Heat Generation, Watts per Animal			
		Basal ^a	Normally Active ^{b,c}		
			Sensible	Latent	Total
Mouse	0.021	0.19	0.33	0.16	0.49
Hamster	0.118	0.70	1.18	0.58	1.76
Rat	0.281	1.36	2.28	1.12	3.40
Guinea pig	0.41	1.79	2.99	1.47	4.46
Rabbit	2.46	6.86	11.49	5.66	17.15
Cat	3.00	7.97	13.35	6.58	19.93
Primate	5.45	12.47	20.88	10.28	31.16
Dog	10.3	20.11	30.71	16.53	47.24
Dog	22.7	36.36	67.60	36.39	103.99
Goat	36	51.39	86.08	42.40	128.48
Sheep	45	60.69	101.66	50.07	151.73
Pig	68	82.65	108.70	85.56	194.26
Chicken	1.82	5.47	3.78	6.42	10.20

^aBased on standard metabolic rate $M = 3.5W^{0.75}$ watt per animal (Kleiber 1961) or appropriate reference (W = animal mass, kg).

^bReferenced according to availability of heat generation data. Otherwise, heat generations is calculated on basis of $ATHG = 2.5M$ (Gordon et al. 1976). Latent heat is assumed to be 33% of total heat and sensible heat is 67% of total heat (Besch 1973, Woods et al. 1972).

^cData taken from Runkle (1964), Kleiber (1961), Besch (1973), Woods and Besch (1974), Woods et al. (1972), Bond et al. (1959), and Ota and McNally (1961).

humidities (35% and 75%), and during light and dark periods. The production rate of CO₂ and H₂O and the consumption of O₂ were constant over the 10 day period once the mice became acclimated to cage conditions (Table 7). However, the generation rate of ammonia depended on the cage relative humidity, light phase, and day in the experiment (Figure 24).

Table 8 lists the approximate amount of heat released by laboratory animals at rest and during normal activity. For load calculation purposes, heat gain from all laboratory animal species can be estimated (Wood et al. 1972, Gordon et al. 1976) with an acceptable level of error from

$$ATHG = 2.5M \quad \text{where } M = 3.5W^{0.75} \quad (9)$$

and where

ATHG = average total heat gain, W per animal

M = basal metabolic rate of animal, W per animal

W = mass of animal, kg

Conditions in animal rooms must be maintained continuously. This requires year-round availability of refrigeration and, in some cases, dual air-conditioning facilities and emergency power for motor drives and control instruments. Chapter 22 of the *ASHRAE Handbook—Applications* has additional information on laboratory animal facilities.

PLANTS: GREENHOUSES, GROWTH CHAMBERS, AND OTHER FACILITIES

Most agronomically important plant crops are produced outdoors in favorable climates and seasons. Greenhouses and other indoor facilities are used for the out-of-season production of horticultural crops for both commercial sales and research purposes, and for producing food, floricultural, and other crops in conditions that permit the highest quality by buffering the crops from the vagaries of weather. The industry that produces crops in greenhouses may be termed controlled environment agriculture (CEA).

Historically, many cold-climate commercial greenhouses were operated only from late winter into early summer, and during autumn. Greenhouses were too warm during midsummer; during winter in some cold-climate locations, light levels were too low and the day length inadequate for many crops. Mechanical ventilation, evaporative cooling, centralized heating systems, movable insulations, carbon dioxide enrichment, and supplemental lighting have extended the use of greenhouses to year-round cropping on a relatively large scale.

Growth chambers, growth rooms, and propagation units are environmentally controlled spaces used for either research or commercial crop production. Environmentally controlled chambers may include highly sophisticated facilities used for micropropagation (e.g., tissue culture), or may be simple boxes in which air temperature and lights are controlled. Indoor facilities having controlled temperature and humidity environments may be used as warehouses to hold plants and plant products prior to commercial sale. Often these are simple refrigerated storage rooms or chambers.

Primary atmospheric requirements for plant production include: (1) favorable temperatures, (2) adequate light intensity and suitable radiation spectrum, and (3) favorable air composition and circulation. Engineering design to meet these requirements typically is based on steady-state assumptions. The thermal and ventilation time constants of most greenhouses are sufficiently short that transient conditions are seldom considered.

TEMPERATURE

Plant Requirements

Leaf and root temperatures are dominant environmental factors for plant growth and flowering. Factors in the energy balance of a plant canopy include air temperature, relative humidity, air movement, thermal radiation exchange, and convective exchange coefficients for sensible and latent heat. Therefore, leaf temperature is affected by such environmental factors as the type of heating and ventilating systems, supplemental lighting, light transmittance characteristics of the greenhouse cover, misting or evaporative cooling, location of the leaf on the plant, and the geometry of the surrounding leaf canopy.

Most information on plant responses to temperature is based on air temperature rather than plant temperature. Leaf temperature is difficult to measure, and one or several leaves represent neither the average nor the extreme temperatures of the plant. Since plants cannot actively regulate their cell and tissue temperatures in response to changing ambient conditions (passive regulation by opening and closing leaf stomata, which controls evapotranspiration, provides a small degree of control), their leaves and stems are usually within a few degrees of the surrounding air temperature (above during times of solar insolation, below at other times due to thermal reradiation and evapotranspiration).

All plants have minimum, optimum, and maximum temperatures for growth. Optimum temperature depends on the physiological process desired. Thermoperiodic species have different optimum day and night temperatures for each stage of growth, and each stage of plant growth may have its own unique optimum temperature

influenced by radiant flux density, the ambient carbon dioxide level, and water and nutrient availability.

Historically, plants have been grown with night temperatures lower than day temperatures. In practice, many greenhouse crops are grown at standard (blueprint) night temperatures. Day temperatures are increased from 5 to 10 K (depending on solar intensity) above night temperatures. [Table 9](#) presents recommended ranges of night temperatures for a selection of greenhouse crops.

Night temperature (NT) and day temperature (DT) are manipulated to provide nonchemical means to control plant height and development in some greenhouse crops. The effects of both DT and NT and their difference ($DIF = DT - NT$) are being investigated. Stem elongation, internode spacing and elongation, rate of elongation, photosynthesis rate, mature stem length, and fruit yield can be affected with DIF control (Jacobson et al. 1998, Neily et al. 1997, Erwin et al. 1991, Moe and Heins 1990). Typically, a negative DIF results in shorter crops. For example, Gent and Ma (1998) increased the yield of greenhouse tomatoes with a larger positive DIF (14 K) as compared to a lower positive DIF (5 K).

Heating Greenhouses

Heat loss from greenhouses is caused primarily by conduction through the structural cover and infiltration of outdoor air. The heating system is designed to meet the sum of the two. Perimeter heat loss is generally only a few percent of the total and is often neglected in design. When movable night insulation is used to conserve energy, heating systems are still designed to match conduction and infiltration losses without insulation because movable insulation may be opened early in the morning when outdoor air temperature is near its minimum, and excess heating capacity may be useful to melt snow in climatic regions where this occurs. Greenhouses are not designed to carry heavy snow loads.

Energy Balance

Radiation energy exchange. Solar gain can be estimated using procedures presented in [Chapter 30](#). Not all insolation appears as sensible heat, however. As a general rule, from two-thirds to three-quarters of ambient insolation is available inside a typical commercial greenhouse. (Highly detailed models for calculating solar transmittance may be found in the literature.) If a greenhouse is filled with mature plants, approximately one-half of the available insolation (transmitted) may be converted to latent heat, one-quarter to one-third released as sensible heat, and the rest either reflected back outdoors or converted through photosynthesis (perhaps 3%).

Supplemental lighting can add significantly to the thermal load in a greenhouse. If movable night insulation is used, venting may be required during times of lighting, even during cold weather. The components of heat addition from supplemental lighting are divided between sensible and latent loads, with approximately one-quarter to one-third of the total heat load in latent form.

Reradiation heat loss from greenhouses comprises complex processes and may involve both reradiation from the structural cover and reradiation from inside the greenhouse if the cover is not thermally opaque. Glass is nearly thermally opaque, but many plastics are not. Newer plastic films may contain IR-inhibiting substances and can save a significant amount of heating energy, while adding only slightly to summer ventilation needs. Condensation on plastic films also reduces transmittance of thermal radiation, while diffusing but not seriously impairing transmittance of solar radiation. Generally, heat loss coefficients used in greenhouse design include the effects of thermal radiation exchange by the structural cover.

Structural heat loss. Conduction q_c plus infiltration q_i determine total heating requirements q_t . While infiltration heat loss is most accurately calculated using enthalpy differences, in practice only air temperature changes are considered, but with the apparent specific heat of air adjusted upward to account for the latent heat component.

Table 9 Recommended Night Temperatures for Greenhouse Crops

Crop Species	Night Temperatures, °C	Remarks	Crop Species	Night Temperatures, °C	Remarks
Aster <i>Callistephus chinensis</i>	10-13	Long days during early stages of growth	Gloxinia <i>Sinningia speciosa</i>	18-21	Lower temperatures increase bud brittleness
Azalea <i>Rhododendron</i> spp.	16-18	Vegetative growth and forcing specific temperatures required for flower initiation and development	Hydrangea <i>H. macrophylla</i>	13-16 16-17 (forcing)	Specific temperature for flower initiation and development
Calceolaria <i>C. herbeohydrida</i>	16 10	Vegetative growth Flower initiation and development; initiation also occurs with long days and high temperatures if photon flux density is high	Iris <i>I. tingitana</i> (Wedgewood)	7-16 (forcing)	Forcing temperature 13 to 14°C for 10/11 bulbs; 10 to 12°C for 9/10 bulbs
Calendula <i>C. officinalis</i>	4-7		Kalanchoe <i>(K. Blossfeldiana)</i>	16	Temperatures influence rate of flower development and incidence of powdery mildew
Calla <i>Zantedeschia</i> spp.	13-16	Decrease to 13K as plants bloom	Lily <i>Lilium longiflorum</i>	16	Temperatures manipulated to alter rate of flower development; specific temperatures for flower initiation
Carnation <i>Dianthus caryophyllus</i>	10-11 winter 13 spring 13-16 summer	Night temperatures adjusted seasonally in relation to photon energy flux density	Orchida <i>Cattleya</i> spp.	16	Temperature requirement of hybrids related in parental species
Chrysanthemum <i>C. morifolium</i>	16 cut flowers 17-18 pot plants	Temperatures during flower initiation especially critical; uniform initiation very important for pot mums; cultivars classified on basis of temperature for development	Orchids <i>Phalaenopsis</i> spp. <i>Cymbidium</i> spp. <i>Cypripedium</i>	18 10 10-13	
Cineraria <i>Senecio cruentus</i>	16 9-10	Vegetative growth Flower initiation and development; plant quality best at low temperatures	Poinsettia <i>Euphorbia pulcherrima</i>	18 16-17	Vegetative growth Photoperiod requirement changes with temperature; bract development influenced by temperature
Crossandra <i>C. infundibuliformis</i>	24-27 18	Germination Growth and flowering	Roses <i>Rosa</i> spp.	16-17	
Cyclamen <i>C. indicum</i>	16-18 13 10-11	Germination Seedlings Growth and flowering	Saintpaulia <i>S. ionantha</i>	18-21	Below 16°C, growth is slow, hard and brittle
Foliage plants	18-21	Species differ in their temperature and radiant energy requirements	Snapdragon <i>Antirrhinum maias</i>	9-10 13-16	Winter Spring and Fall seedlings benefit from 16 to 18°C temperatures
Fuchsia <i>F. hybrida</i>	11-16	Long days for flower initiation	Stock <i>Matthiola incana</i>	7-10	Buds fail to set if temperatures are above 18°C for 6 h or more per day. Grown mainly as field crop
Geranium <i>Pelargonium hortorum</i>	11-16	16 to 18°C for fast crops at high radiant energy flux	Tomato	16-19	Dry temperatures from 21 to 27°C on sunny days
Gardenia <i>G. grandiflora</i> <i>G. jasminoides</i>	16-17 16-17	Lower temperatures result in iron chlorosis; higher temperatures increase bud abscission	Lettuce	13	17 to 18°C on cloudy days 21 to 26°C on sunny days
			Cucumber	18	24°C on cloudy days 27°C on sunny days

Table 10 Suggested Heat Transmission Coefficients

		$U, \text{W}/(\text{m}^2 \cdot \text{K})$
Glass	Single-glazing	6.4
	Double-glazing	4.0
Plastic film	Manufacturer's Data	
	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

^aInfrared 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.

^bPlastic structured sheets are double-walled, rigid plastic panels.

Table 11 Typical Infiltration Rates for Various Construction Types (ach)

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

$$q_t = q_c + q_i \quad (10)$$

$$q_c = \sum UA\Delta t \quad (11)$$

$$q_i = c_p V \left(\frac{N}{3600} \right) \Delta t \quad (12)$$

where

U = heat loss coefficient, $\text{W}/(\text{m}^2 \cdot \text{K})$ (Table 10)

A = exposed surface area, m^2

Δt = inside minus outside air temperature, $^{\circ}\text{C}$

c_p = volumetric specific heat of air (adjusted upward to account for latent heat component), $0.5 \text{ kJ}/(\text{m}^3 \cdot \text{K})$

V = greenhouse internal volume, m^3

N = number of air exchanges per hour (Table 11)

Σ = summation of all exposed surfaces of the greenhouse and perimeter heat losses

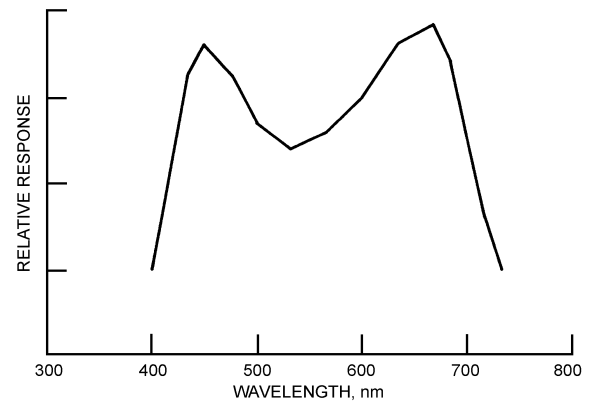
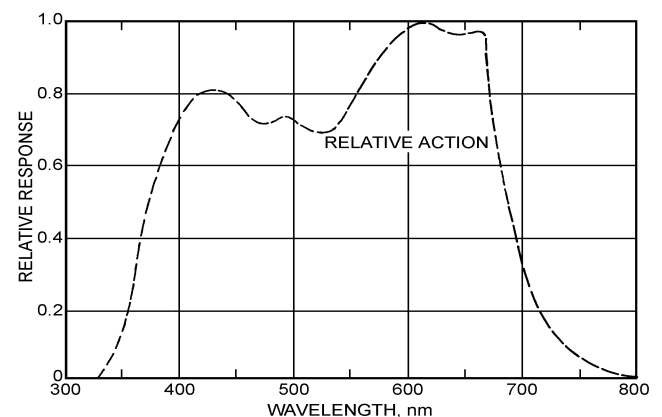
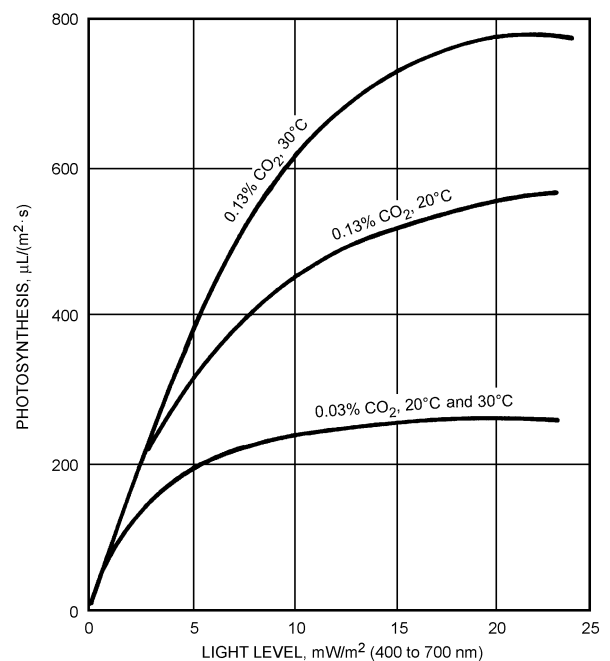
When design conditions are assumed for indoor and outdoor air temperatures and air exchange rate, the resulting heat loss may be assumed equal to the peak heating requirement for the greenhouse.

No universally accepted method exists to determine season-long heating needs for greenhouses. The heating degree-day method may be applied, but heating degree-day data must be adjusted to a base lower than 18.3°C because of the significant passive solar heating effect in greenhouses. The proper base must be determined locally to reflect the expected solar climate of the region and the expected greenhouse operating temperature. These difficulties often lead designers to obtain season-long heating data from comparable, existing greenhouses in the region, and apply them to new designs.

LIGHT AND RADIATION

Plant Requirements

Light (400 to 700 nm) is essential for plant vegetative growth and reproduction (Figure 25 and Figure 26). Intensity integrated over time provides the energy for growth and development, while

**Fig. 25 Traditional Photosynthesis Action Spectra Based on Chlorophyll Absorption****Fig. 26 Relative Photosynthetic Response****Fig. 27 Photosynthesis of Cucumber Leaf at Limiting and Saturating Carbon Dioxide Concentrations under Incandescent Light**

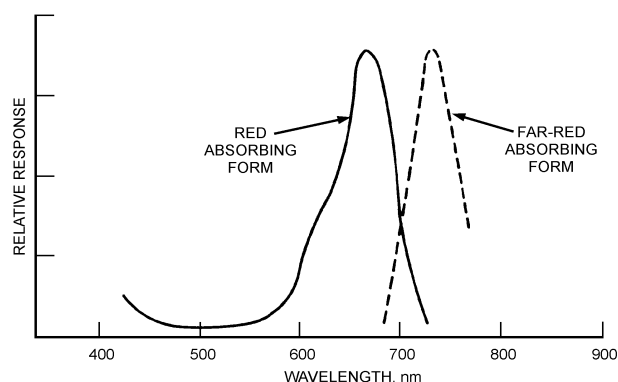


Fig. 28 Phytochrome Action Spectra

duration (either long or short, depending on species) may be essential for certain physiological processes such as flowering. High light intensity may exceed the ability of individual leaves to photosynthesize. However, if there is a dense canopy, excess light may be beneficial to lower leaves even when upper leaves are light saturated. The intensity at which light saturates a leaf depends on various environmental factors, such as the concentration of carbon dioxide in the ambient air, as well as biological factors (Figure 27).

Spectral distribution of light can affect plant development, but sunlight's spectral distribution need not be duplicated by artificial lighting to have suitable growth and development. Certain reproductive changes are initiated by red (660 nm) and far red (730 nm) light (Figure 28), and excessive ultraviolet light (290 to 390 nm) may be detrimental to growth.

Plants that respond to the durations of light and dark periods are termed photoperiodic (photoperiodic effects generally relate to flowering). Some plant species are long-day obligates, some are short-day obligates, some are day length-intermediate, and others are day-neutral. Such responses are usually (relatively) independent of light intensity. Photoperiodic effects can be initiated by very low light levels (less than 1 W/m²), such as that provided to chrysanthemums by incandescent lights for a short period during the middle of the night to promote vegetative growth and inhibit flowering (until a suitable size has been attained) during the winter. Some plant species can tolerate continuous light, but others require some period of darkness for proper growth and development.

Sunlight is the most common source of photosynthetically active radiation (PAR, 400 to 700 nm). Although specially designed lamp sources may provide light similar to sunlight, no single source or combination of sources has spectral radiation exactly like the emission of the sun from 300 to 2700 nm. Table 12 summarizes the spectral distribution of various light sources. Three systems of measuring radiation are as follows:

1. Radiometric units (irradiance) in watts per square metre (W/m²), with specified wavelength intervals.
2. Quantum units as photon flux density in $\mu\text{mol}/(\text{s} \cdot \text{m}^2)$ (at 400 to 700 nm unless otherwise specified). A mole of photons delivered in one second over a square meter may be called an einstein.
3. Photometric units (illuminance) as one lumen per square metre, or lux (lx).

Plant scientists use photosynthetic photon flux density (PPFD) in $\mu\text{mol}/(\text{s} \cdot \text{m}^2)$ (400 to 700 nm). Engineering organizations and manufacturers of light sources use photometric and radiometric units. Because of the variation in spectral power distribution, conversion from one system of units to another must be made individually for each light source for the wavelength interval included (Table 13). To obtain comparable plant growth from different light sources, the same radiation levels (PAR) and red/far-red ratios must be maintained.

Table 12 Radiation Power Distribution of Light Sources

Light Sources	UV 300- 400 nm	PAR + FAR 400- 850 nm	IR 850- 2700 nm	Thermal 2700 + nm	Total Radiation
FCW	2	36	1	61	100
HG/DX	3	19	18	60	100
MH	4	41	8	47	100
HPS	0.4	50	12	38	100
LPS	0.1	56	3	41	100
INC	0.2	17	74	9	100
SUN	6	59	33	2	100

Values are in watts per 100 W of radiation.

Table 13 Light Conversion Factors

Light Source	Multiply W/m ² (400-850 nm) to Obtain:	Divide lux by Constant to Obtain:	
	$\mu\text{mol}/(\text{s} \cdot \text{m}^2)$ (400-700 nm)	$\mu\text{mol}/(\text{s} \cdot \text{m}^2)$ (400-700 nm)	$\mu\text{mol}/(\text{s} \cdot \text{m}^2)$ (400-850 nm)
Sun and sky, daylight	4.57	54	36
Blue sky only	4.24	52	41
High-pressure sodium	4.98	82	54
Metal halide	4.59	71	61
Mercury deluxe	4.52	84	77
Warm white fluorescent	4.67	76	74
Cool white fluorescent	4.59	74	72
Plant growth fluorescent A	4.80	33	31
Plant growth fluorescent B	4.69	54	47
Incandescent	5.00	50	20
Low-pressure sodium	4.92	106	89

Adapted from Thimijan and Heins (1983).

Radiation Levels for Plant Growth

Display 0.3 W/m². For display purposes, plants can exist at an irradiance of 0.3 W/m². The preferred lamp has changed with technological advances in efficiency and distribution. The emphasis, however, has always been on color rendering and the type of atmosphere created in the display space. Low-wattage incandescent and fluorescent lamps are preferred. At this irradiance, plants can be displayed (seen), but little or no significant positive effect on plants can be expected. Extended holding in such low light conditions will have a negative effect on many plant species. Timing (light-dark durations) and temperature interaction are not a concern.

Photoperiod Response 0.9 W/m² (4 to 6 h). For a photoperiod response, plant growth can be regulated at an irradiance of 0.9 W/m² for as little time as 1 h. This irradiance is called a low light intensity system. The range of plant responses (promote or delay flowering, promote growth) that can be regulated is extensive, and this lighting is widely used by commercial growers.

Survival 3 W/m² (8 h). Plants can survive at an irradiance of 3 W/m² for 8 or more hours daily. This level enables many green plants to maintain their color. However, stem lengthening (etiolation) and reduction in new leaf size and thickness occur under this irradiance level. In time, the overall development of the plants falls behind that of other plants grown under higher radiation levels. Photoperiod responses do not function well at this irradiance. However, strong interactions occur between this irradiance and temperature, watering frequency, and nutrition. Cooler temperatures (less than 17°C) help conserve previously stored material, while frequent watering and fertilization aggravate stem lengthening and senescence of older foliage.

Growth Maintenance 9 W/m² (12 h). Plants maintain growth over many months when exposed to an irradiance of 9 W/m² of 12-h duration daily. This is the intensity at which many indoor gardeners (professional or hobbyists) grow their plants when

starting them from seeds, cuttings, or meristems. Interactions with the environment (temperature, airflow, relative humidity, and pollutants) can vary among installations. Simple facilities with good air exchange and limited lamp concentration can grow a wide range of plant species. The rate of development, particularly as the plants grow in size, can be slow compared to plants grown at higher irradiances.

Propagation 18 W/m² (6 to 8 h). Plants propagate rapidly when exposed to an irradiance of 18 W/m² for a minimum of 6 to 8 h daily, but they prefer 12 h. Above this level, many propagators attempt to shade their greenhouses with one or several layers of neutral filters (painted films on glazing, or movable or semipermanent plastic or other fabric shade cloth materials) to restrict light (and heat) in the propagation area.

Cuttings rooted at this intensity maintain a growth rate much like that of similar tissue on a stock plant. Stem length, branching, and leaf color, however, can be regulated by manipulating temperature, moisture, stress, and nutrients. Most plants grown for their flowers and fruits can be brought to maturity by increasing the day length to 16 to 18 h for flower initiation (or rapid growth) and then reducing the day length to 8 to 12 h for development. The growth rate, however, is relatively slow. For quickest development (leaf number, number of branches, and early flower initiation), the plants must be transferred to a higher lighting regime—24 to 50 W/m².

Greenhouse Supplemental Light 24 W/m² (8 to 16 h). When natural light is inadequate, it may be supplemented up to approximately 24 W/m² for 8 to 16 h daily. When coupled with the ambient sunlight (shaded by clouds, greenhouse structures, and lamp fixtures), this irradiance simulates many of the growth responses and rates associated with growth chamber studies. Plants grown in greenhouses without supplemental lighting grow slower and flower later than lighted ones in cloudy regions or in northern areas during winter. Duration (in hours) and timing (day-night) of lighting is critical.

Supplemental lighting for 8 h, particularly during the day (0800 to 1600) may not be as cost-effective as lighting at night (2000 to 0400) if off-peak electric rates are available. Neither of these lighting regimes, however, is as effective as lighting for 16 h from morning to midnight.

Lighting short-day plants, such as chrysanthemums and poinsettias, is relatively inefficient because they can be lighted only during the 8- to 12-h day, followed by an obligatory 12- to 16-h daily dark period.

Growth Chambers 50 W/m² (8 to 24 h). Plants grow in growth chambers or growth rooms if the light irradiance is a minimum of 50 W/m² for 8 to 24 h daily. This irradiance is approximately one-fourth that of outdoor sunlight. Cool, white fluorescent lamps, combined with incandescent lamps, are widely used. More recently, HID lamps have been substituted for fluorescent lamps. For consistent results, all require a barrier of glass or other material between the lamp and the plants, and a separate ventilating system to remove the heat from such enclosed spaces.

Since filters cannot remove infrared completely, chambers are difficult to standardize. This often leads to confusing information on plant growth and flowering of plants grown in greenhouses and outdoors. When the total irradiance is 50 W/m² and 10 to 20% of the total radiation is provided by incandescent lamps, most kinds of plants can be grown. In typical plant forms, flowering and fruiting responses occur when the plants are subjected to the following parameters:

- Day length, 8 to 24 h
- Temperature, 10 to 35°C
- Carbon dioxide, 300 to 2000 ppm (540 to 3600 mg/m³)
- Relative humidity, 20 to 80%

Photoperiod

Day length affects the performance of some plants. There are four basic day length plant groups:

1. *Short-day plants* flower only when the length of the daily light period is less than the critical number of hours. Daily light periods longer than the critical length inhibit flowering.
2. *Long-day plants* flower only when the daily light period is longer than the critical number of hours. They become dormant or remain vegetative when the daily light period is shorter than the critical length.
3. *Day length-intermediate plants* flower only within a narrow range of day length, usually between about 10 and 14 h. If the day length is shorter than the optimum day length for flowering, the plants stop growing.
4. *Day-neutral plants* continue in vegetative growth or flower regardless of the day length.

Continuous light inhibits flowering and promotes vegetative growth of short-day plants, but encourages continued vegetative growth and early flowering of long-day plants, blocks the flowering of day length-intermediate plants, and in many instances, increases the stem length of day-neutral plants. Plants vary in their responsiveness to light source, duration, and intensity. The technology that has evolved to control the photoperiod of plants is based primarily on the incandescent-filament lamp. Of all the light sources available, this lamp creates the regulating mechanism most similar to that of sunlight. This is because the red/far-red wavelength ratio of light from an incandescent lamp is similar to the ratio of sunlight.

The effectiveness for photoperiod response in plants peaks at wavelengths of 660 nm (red) and 730 nm (far-red). The relative order of activity in regulating photoperiod responses by lamp type is as follows: Incandescent (INC) > High-pressure sodium (HPS) >> Metal halide (MN) = Cool white fluorescent (F) = Low-pressure sodium (LPS) >> Clear mercury (Hg). Photoperiod lighting is always used in combination with daylight or another main light source. Short days (less than normal day length) are created in the greenhouse with opaque materials that surround the plants.

RELATIVE HUMIDITY

Relative humidity affects the rate at which plants take water up, the rate of latent heat transfer, and certain diseases. Normal plant growth generally occurs at relative humidities between 20 and 80% if the plants have a well-developed root system, although relative humidities above 40% are preferred to avoid water stress conditions.

Transpiration, the movement of water vapor and gases from the plant to its surroundings, is controlled by the plant's stomatal openings. It is a function of air velocity and the vapor pressure difference between water at saturation at the leaf temperature and the actual water vapor partial pressure in the air. Generally, as relative humidity decreases, transpiration increases. Very low relative humidities (less than 20%) can cause wilting, since evaporation losses may be higher than the plant can replace, especially when light intensity is high.

High humidity provides a good environment for pathogenic organisms. Many pathogenic spores do not germinate unless relative humidity is 96% or more and many require a film of water on the leaves. Somewhat lower relative humidities may support other pathogen growth stages.

Still air surrounding a plant may be much wetter than the general atmosphere because evapotranspiration from the leaves raises the relative humidity in interfoliage air. The lower leaves, which stay moist longer, are more susceptible to disease. The upper leaves are dried by radiation and air currents.

AIR COMPOSITION

Carbon dioxide, which comprises about 0.035% of ambient air, is essential for plant growth. There are basically three ways to obtain carbon dioxide for greenhouse enrichment: pure in solid, liquid, or gaseous form; from burning fuels such as propane, natural gas, or kerosene; and by the aerobic breakdown of organic matter. The three ways are listed in order of purity and reliability. Carbon dioxide enters plants through stomata and is converted to carbohydrates through photosynthesis. The carbon dioxide concentration in air surrounding a plant, as well as light level, affects the rate of photosynthesis. The concentration for maximum growth depends on many factors, including the stage of growth, leaf area, light intensity, temperature, and air velocity past the stomatal openings.

An important relationship exists between light level and carbon dioxide uptake (Figure 27). As light level increases, carbon dioxide concentration must increase concurrently to take maximum advantage of the greater photosynthetic potential. In plastic greenhouses, and in glass greenhouses sealed against infiltration, the carbon dioxide level can drop below 360 mg/m³ when the weather is cold, light levels are moderate, and the greenhouse is not ventilated. Carbon dioxide enrichment just to maintain normal levels can then be beneficial. During times of high light levels, carbon dioxide enrichment gives maximum benefit from the available light and may even be economically desirable when greenhouse ventilation is modest. However, carbon dioxide concentrations above 2700 mg/m³ are seldom recommended; levels between 1400 and 2200 mg/m³ are typically used.

The effects of enrichment are not always positive. Without proper crop management, the yield, quality, or both may decrease, and timing of crop maturity may change.

Pollutants

Plants are sensitive to atmospheric pollutants such as ethylene, ammonia, gaseous fuels, ozone, fluorides, photochemical smog, and oxidants (from nitrogen and sulfur). Pollution damage can range from small spots on leaves, to yellowing of leaves, to severe foliage burn, and, ultimately, to plant death in extreme but not rare situations. The effect occurs both outdoors and in greenhouses; however, this is more common in greenhouses, because of their closed nature. Pollutants indoors can be removed by activated charcoal filters in the ventilation system; however, these are seldom used in commercial greenhouses. Economically, the more feasible approach is to limit pollutant production within, or introduction into, the greenhouse air space.

Ethylene is produced naturally by plants and leads to flower and whole plant senescence. It is also produced by combustion of gaseous and liquid fuels and can rapidly cause plant damage. Concentrations above 230 µg/m³ can have a detrimental effect on plant growth. Unvented heaters, air currents that bring vented combustion products back into the greenhouse, and burners for carbon dioxide production are common sources of ethylene injury. Liquefied carbon dioxide may be used to supplement natural levels rather than combustion, specifically to avoid introducing ethylene into the greenhouse air, but even liquefied carbon dioxide should be carefully selected to avoid residual amounts of ethylene that may be contained within it.

Nitrogen oxides, common components of air pollution, can cause serious plant damage. Greenhouse locations near highways, nearby industrial complexes, and even a truck left running for an extended time near a greenhouse air intake vent may lead to leaf damage from NO and NO₂.

Sulfur dioxide, produced by the burning of sulfur containing fuels, causes injury to many plants within a short time. Sources of sulfur dioxide may be nearby, such as an industrial area, or may be within the greenhouse complex, such as the vented combustion products from a central heating facility, combustion products from

carbon dioxide burners (using kerosene as a fuel, for example), and sulfur burned for mildew control.

Ozone is widely recognized as a serious pollutant affecting the production of many agronomic crops. Although few research results exist to quantify the effect of ozone on greenhouse crops, damage is likely to occur when greenhouses are located near ozone sources.

Phenolics and certain other organic vapors are phytotoxic. Phenolics, as volatiles from certain wood preservatives (creosote and pentachlorophenol), can cause leaf and petal damage. Vapors from some paints can also be damaging. Misuse of herbicides and pesticides can lead to plant injury, either through spray drift or volatilization.

Covering and sealing greenhouses for energy conservation can increase concentrations of ethylene and other air pollutants if their sources are within the air space, since infiltration and ventilation are decreased. Sealing to reduce infiltration can also lead to rapid carbon dioxide depletion and inhibited plant growth during cold temperatures when, even with bright light, ventilation is not required.

AIR MOVEMENT

Air movement influences transpiration, evaporation, and the availability of carbon dioxide. Air speed affects the thickness of the boundary layer at the leaf surface, which in turn influences the transport resistance between the ambient air and the leaf stomatal cavities. Air speed of 0.5 to 0.7 m/s is commonly accepted as suitable for plant growth under CEA conditions. Air speeds across the leaf of 0.03 to 0.1 m/s are needed to facilitate carbon dioxide uptake. Air speeds above 1 m/s can induce excessive transpiration, cause the stomatal guard cells to close, reduce carbon dioxide uptake, and inhibit plant growth. Air speeds above 5 m/s may cause physical damage to plants. Generally, if plants within a greenhouse move noticeably due to ventilation, air speed is excessive.

Air circulation within greenhouses may be created to reduce thermal stratification and maintain suitable levels of carbon dioxide within the leaf canopy. Horizontal air flow, produced by small propeller fans that move air around the greenhouse in a racetrack pattern, has been found to be effective. Such fans are approximately 350 mm in diameter, with approximately 0.2 kW motors, spaced at approximately 15 m intervals. Total fan capacity in metres per second (m³/s) should equal about 25% of the greenhouse volume in cubic metres.

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