12

Controlled-Environment Horticulture

Purpose and Expected Outcomes

This chapter is designed to show that plants may be grown outside of their natural environments by providing all of the growth requirements needed and to describe the facilities required for such a plant cultivation practice.

After studying this chapter, the student should be able to

1. Discuss different designs, construction materials, and locations of greenhouses.
2. Describe the methods of controlling indoor plant growth factors (light, temperature, moisture, nutrients, and air) for the benefit of crops.
3. Describe how greenhouses are used in the production of horticultural plants.
4. Compare and contrast greenhouse and field production of crops.

[COLOR PLATES—*see color plates 17 and 18* for additional chapter photos]

Section 1

Controlled-Environment Facilities and Their Operation

Overview

Plants, like other living organisms, have certain requirements for growth. Climatic conditions are not uniform throughout the world. As such, certain plants are grown or found in nature only in certain regions (i.e., plants are adapted to certain environments). Some plants are more restricted in their range of adaptation. The general principle in choosing plants is that if you desire to grow a plant outside of its region of natural adaptation, you must provide all of the necessary growth requirements (above- and belowground conditions [Chapter 4]) in the new growing environment. Sometimes supplementation of natural conditions such as the provision of additional light is necessary.

In tropical regions of the world where growing seasons are longer, growing flowers indoors is not as popular as growing them outdoors. Outdoor flower gardens can be enjoyed for longer periods of time. On the contrary, the growing season in temperate climates is much shorter. Flowers do not grow outdoors in the cold winter months, which may last more than six months in some areas. In such regions, people desire to grow plants indoors under artificial conditions.

To enjoy flowers or horticultural products out of season, plants must be grown in a *controlled environment,* meaning that humans, not nature, determine how the conditions change. Growers can create stable microclimates that are ideal for specific plants. Otherwise, flowers or crops can be produced elsewhere in due season and imported into an area where the plant is out of season. Although some of this import-export trade in flowers and other horticultural products occurs, the ready availability of controlled-environment structures or facilities called *greenhouses* has spawned an industry that produces off-season ornamentals and vegetables for local and distant markets. This chapter is devoted to the greenhouse industry and discusses its advantages, limitations, design, operation, and maintenance. The culture of plants in liquid media *(hydroponics)*, perhaps the ultimate in controlled-environment production, is also discussed.

12.1 What Is a Greenhouse?

Greenhouse
A structure with transparent covering that is used for growing plants under controllable conditions.

A **greenhouse** is a specially constructed building for growing plants under controlled conditions. It is covered with a transparent material and as such permits entry of natural light. The building has no green color but perhaps gets its name from the fact that (green) plants are grown in it. Greenhouses differ in design, size, and the extent of environmental control. Some of the simplest ones are capable of controlling temperature and light. Others are fitted with state-of-the-art computer-based equipment for controlling humidity, light, temperature, nutrients, and soil moisture. In Europe, a greenhouse is called a *glasshouse.*

Small-scale and simply equipped greenhouses are used for the domestic culture of houseplants. Greenhouses are a necessary feature of the horticultural nursery operation, even when plants are grown in season. Commercial greenhouses are widely utilized to produce premium-quality fruits, vegetables, and ornamentals by providing optimal growth conditions for these plants.

12.2 Greenhouse Design and Construction

The most prominent feature of a greenhouse is how it is designed to take advantage of sunlight. As such, except for the foundation, a short wall (called a *curtain wall*) erected above it, and the metallic frame, a greenhouse consists of a transparent material (e.g., glass, plastic film, or fiberglass-reinforced plastic) that freely admits natural light.

12.2.1 TYPES OF GREENHOUSES

There are three basic types of greenhouses: attached, detached (freestanding), and connected. These types of greenhouses are constructed according to one of several styles. The older styles include the following:

1. Even-span
2. Uneven-span
3. Lean-to
4. Quonset
5. Gothic arch

6. Curvilinear
7. Curved eave
8. Dome

Quonset is the most common detached greenhouse design for commercial production. Though suitable for most crops, the growing area and hence productivity is reduced because of the arching of the side walls.

Modern greenhouses are highly sophisticated with a significant amount of automation of operations for increased efficiency. In addition to the modifications and modernizations of older styles of greenhouses, there are newer greenhouse designs concepts, such as the open roof design (Figure 12–1).

Attached Greenhouses

A greenhouse is attached if part of it is connected to a building. *Attached greenhouse* designs and construction are usually simple. They are less expensive to construct because one side is preexisting, which cuts down on the amount of materials needed. However, because they are connected to existing structures, their sizes and uses are affected by the characteristics of the buildings to which they are attached. The buildings may shade the greenhouse at some time of day. Further, light control and ventilation may be problematic. Attached greenhouses are not used for commercial production but are found in homes, commercial buildings, garden centers, and where plant displaying is needed.

A style of greenhouse that is specifically designed to be attached is the *lean-to greenhouse* (Figure 12–2). The ridge of the roof is attached to the preexisting wall such that the roof slopes away from the wall. Lean-to greenhouses are small in size and best

FIGURE 12–1 An open-roof greenhouse used for research at Rutgers University. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

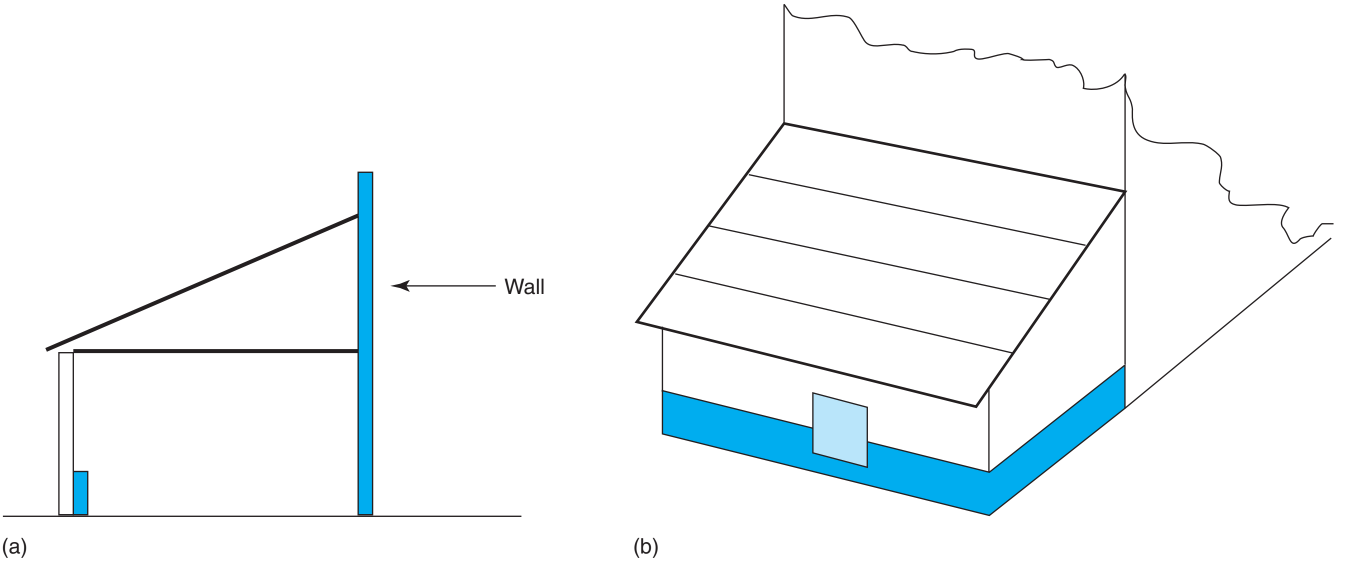

FIGURE 12–2 A lean-to greenhouse:(a) side view and (b) front view.

located on the south side of the building to take advantage of sunlight. Where more space exists, the even-span style (see later section) may be adopted. A lean-to greenhouse may also be window mounted.

Detached Greenhouses

As the name implies, *detached greenhouses* are designed to be freestanding and thus are sometimes called by that name. None of the walls or the roof are attached to a preexisting structure. A detached greenhouse can thus be located such that it takes maximum advantage of environmental factors such as light and wind. Environmental regulation is easier in detached than in lean-to styles. The most common style of greenhouse is the *freestanding even-span greenhouse.* Also called the *A-frame,* this style consists of a symmetrical roof. The even-span, or A-frame design, is the most common design for a glass greenhouse. An even-span design has a symmetrical roof whose slopes have equal pitch and width. The American-style A-frame design has a larger roof surface area (Figure 12–3), and the Dutch design has small gables and a smaller roof surface area (Figure 12–4).

Another detached greenhouse style is the *uneven-span* design (Figure 12–5). This design has asymmetrical roof slopes of unequal pitch and width. While it is adaptable to hillsides or slopes, it does not readily lend itself to modern greenhouse automation and as such is not commonly used.

Greenhouse roofs may be arched, as in the *Quonset* design (Figure 12–6) or the *Gothic arch* design (Figure 12–7). The former design is quite commonly used, while the latter is not.

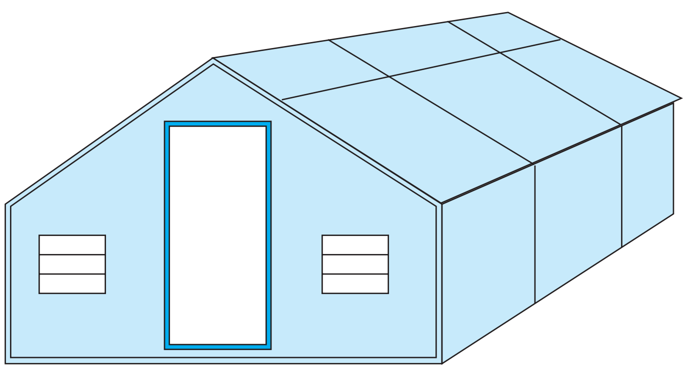

FIGURE 12–3 A freestanding even-span American design greenhouse.

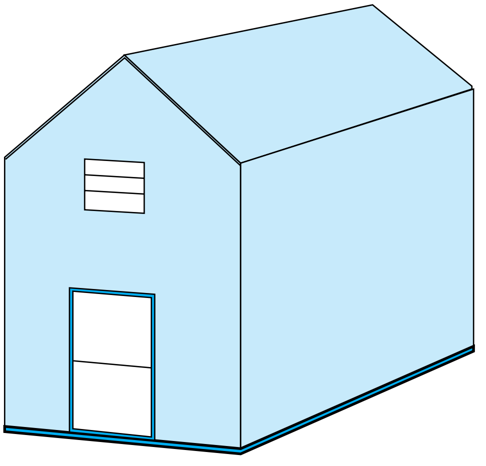

FIGURE 12–4 A freestanding even-span Dutch design greenhouse.

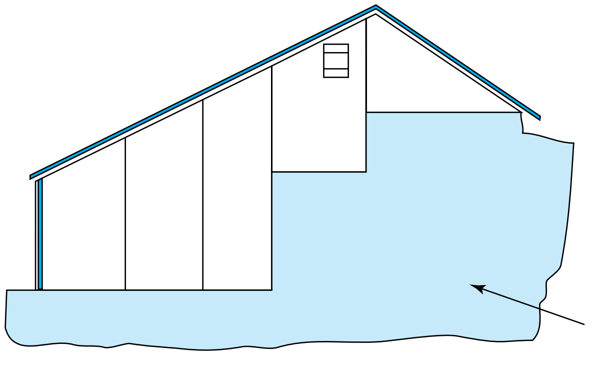

FIGURE 12–5 An uneven-span greenhouse design.

FIGURE 12–6 A Quonset greenhouse design. *(Source: George Acquaah)*

Detached greenhouses have several advantages. Environmental control is easier and can be programmed to meet the needs of a specific production operation. Ventilation is easy to implement, thus limiting carbon dioxide buildup, which can be a limiting factor in plant growth during winter. General operation and maintenance is relatively easier in detached greenhouse designs than attached designs. However, because of their generally vaulted ceilings, they are less energy efficient, increasing operating costs in winter.

Gutter-Connected Greenhouses

Greenhouses of one style can stand alone and are called *Single Span.* Several greenhouses of one style may be joined together to form a *connected greenhouse or Multi span (gutter-connected).* These greenhouse units are joined along the eaves to create a large, undivided space for a large operation. This arrangement makes the buildings more economical to heat on a per-unit-area basis. Since the junction between two adjacent eaves creates a gutter, *ridge-and-furrow* designs (Figure 12–8) may be in danger of stress from accumulation of snow where this weather pattern exists. Their design takes this potential problem into account by the installation of heating pipes in these depressions to melt away any accumulation of snow when it occurs. Ridge-and-furrow designs are suited to greenhouse production enterprises that require similar environments. When used for smaller projects requiring unique environmental conditions, this type of greenhouse must be partitioned. When Quonset greenhouse units are connected, they form a *barrel-vault greenhouse* (Figure 12–9). Similarly, several lean-to greenhouse units

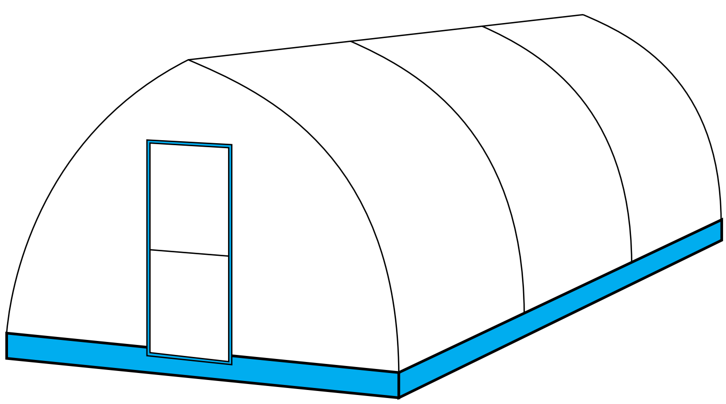

FIGURE 12–7 A Gothic arch-style greenhouse design.

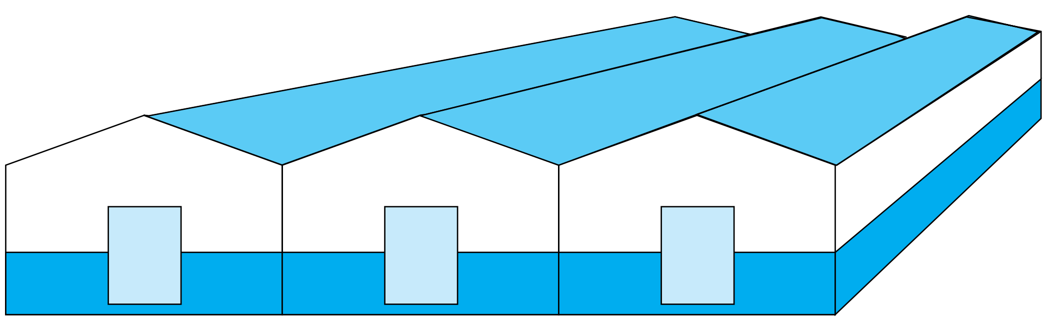

FIGURE 12–8 A ridge-and-furrow greenhouse range.

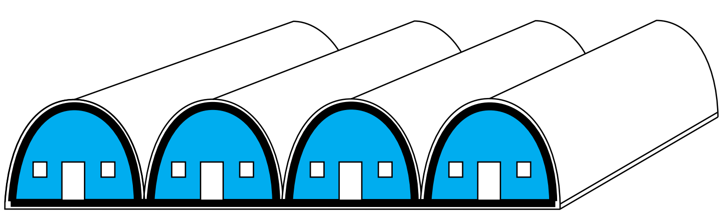

FIGURE 12–9 A barrel-vault greenhouse range.

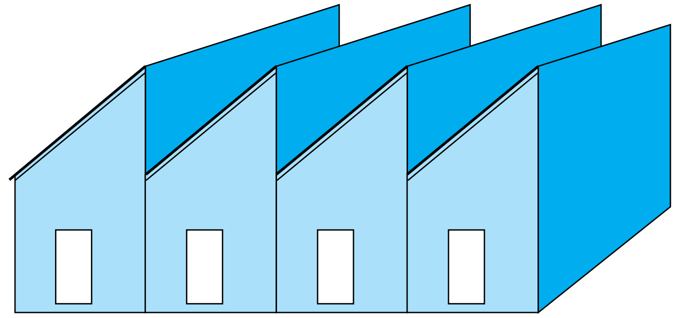

FIGURE 12–10 A saw-tooth greenhouse range.

may be connected to form a saw-tooth greenhouse (Figure 12–10). *Saw-tooth greenhouses* are used in places such as Texas, Florida, and California, where the climate is mild. Large nurseries, for example, may construct a number of greenhouses on one site to form what is collectively called a **greenhouse range.**

Greenhouse Range
A collective term for two or more greenhouses at a single location belonging to the same owner.

The construction costs of connected greenhouses are higher than freestanding designs. The roofs are longer and thus require more structural strength in the framework to support the building. They are also lower, and hence the volume of air space is less, decreasing the amount of carbon dioxide available for plants in winter.

Greenhouses may also be categorized based on the material used in their construction. These materials may further be grouped according to those used in the framework of the structure and those used for framing or covering the structure. Greenhouses may be arranged in multiple units to form large complexes. All of these styles, arrangements, and types of materials have advantages and disadvantages. These characteristics are discussed further later in this section.

12.2.2 GREENHOUSE CONSTRUCTION

The material used for greenhouse construction must be strong, light, durable, easy to maintain, and inexpensive. It is important that the frame cast little shadow.

The basic structural components of a greenhouse are the rafter, end walls, sidewall, sidepost, and purlins. The National Greenhouse Manufacturers Association publishes standards to guide greenhouse design.

Material for Framework

The frame of a greenhouse may be made of metal or wood.

Metal Metal frames are more durable but relatively more expensive than wooden frames. Iron frames are prone to rust and need to be painted (usually white) at regular intervals to prevent rust. Aluminum frames are lightweight and rust resistant. Since the material is very strong, greenhouse designs incorporate fewer and more widely spaced *sash bars* (beams used to support glazing or covering material without sacrificing the overall sturdiness of the structure. Further, wider spacing of the sash bars means less shading from obstruction of incoming light.

Wood Wood was used in early greenhouse designs. It is relatively less expensive but also less durable than metal. Wood decays over time and is susceptible to insect attacks (e.g., termites). Like iron, wood requires painting (greenhouse paint) to protect it from decay and insect attack. Durable species of wood are redwood and cedarwood. For longer life, wood may be treated with preservatives before use. Mercury-based paints are toxic to plants and must not be used. Similarly, pentachlorophenol and creosote wood treatments are toxic to plants. Since wood is not as strong as metal, spacing of sashes in wooden greenhouses is much closer, especially if heavyweight glazing material (e.g., glass) is to be used. Closer sash spacing means an increased shading from obstruction of incoming light.

12.2.3 FRAME DESIGN

There are two basic frame designs: A-frame (gabled) and arched-frame greenhouses (curved arch). The gabled types are more expensive to construct.

A-Frame Greenhouses

In A-frame design, most of the weight of the greenhouse rests on the *side posts,* which are often encased in concrete. These erect posts support the *truss* (consisting of *rafter, strut,* and *chords*). The trusses on either side meet at the peak (ridge) of the roof. Series of trusses are connected by long bars *(purlins)* that run the length of the greenhouse. The end view presents an A-shaped structure called a *gable* (Figure 12–11). The bottom 2 to 3 feet (0.6 to 0.93 meters) of the greenhouse above the ground consists of a wall called the curtain wall, which is made out of materials such as cement or concrete blocks. The curtain wall is the structure to which heating pipes are usually attached. Sash bars are attached to purlins as anchors for panes.

Arched-Frame Greenhouses

In arched-frame greenhouse designs, the trusses are pipes that are bent into an arch and connected by purlins (Figure 12–12). This design is called a Quonset.

12.2.4 GLAZING (COVERING) MATERIAL

The most important role of **glazing** or covering material is transmittance of light. No material can transmit 100 percent of all of the light that strikes its surface. It is hoped that most of the light will be transmitted through the material, but some of it will be absorbed or reflected back into the atmosphere. The materials used for glazing are described in the

Glazing
A transparent material used to cover a greenhouse frame.

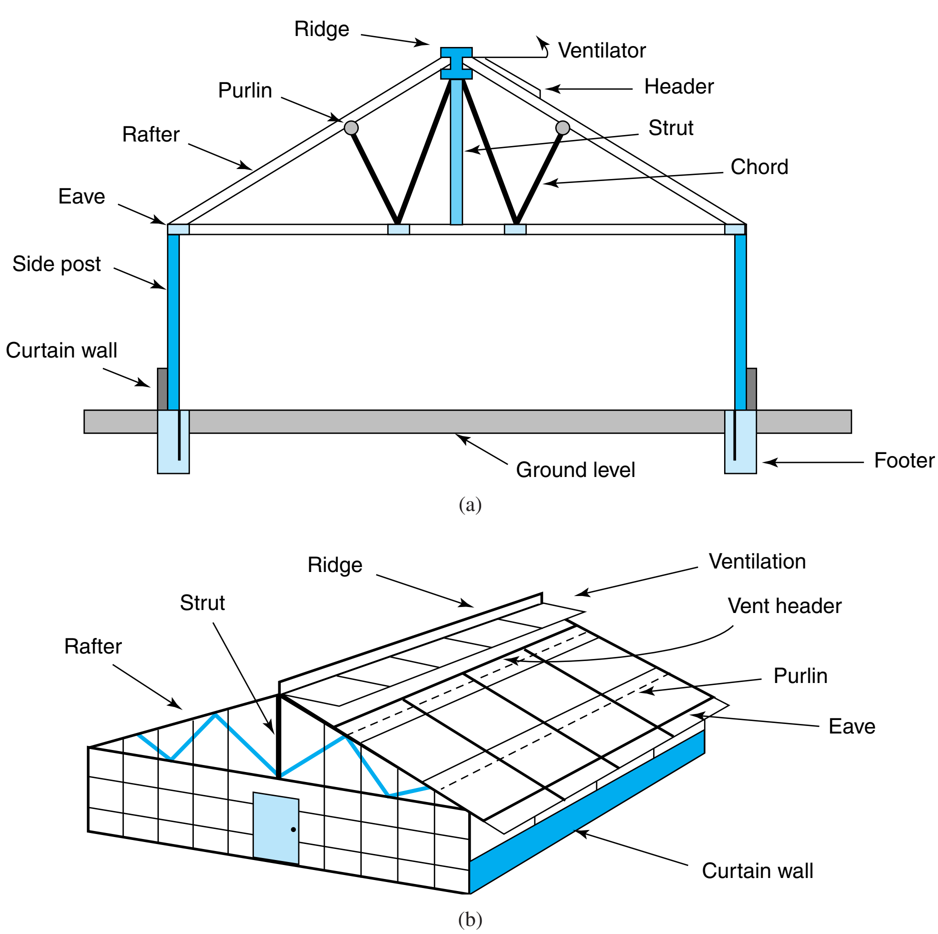

FIGURE 12–11 A-frame greenhouse structure: (a) end view and (b) general view.

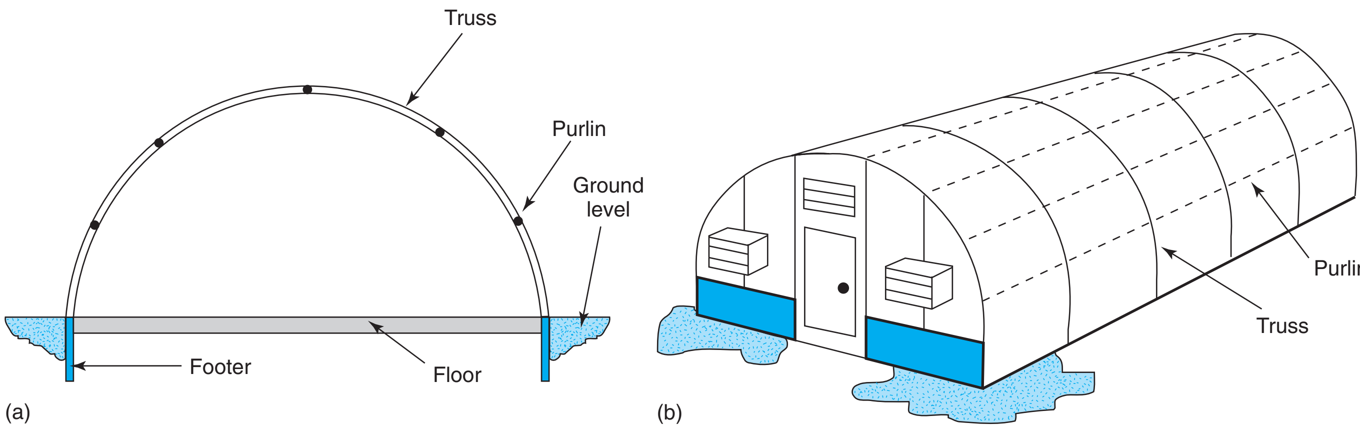

FIGURE 12–12 Arched-frame greenhouse structure: (a) end view and (b) general view.

following sections. The dominant material used varies among the states. In most cases, the single most important glazing used is film plastic.

Glass

Glass is about 70 percent silica dioxide (SiO_2). However, it contains other oxides, including iron trioxide (Fe_2O_3), which may be present at a level between 0 and 1.15 percent. The amount of light glass transmits depends on the iron content; the higher the iron content, the lower the transmittance. Glass used to glaze greenhouses does not transmit light in the ultraviolet (UV) range of the light spectrum. Glass greenhouses, the first to be commercially constructed and still popular today, are durable, lasting more than twenty-five years. Glass transmits about 90 percent of the sunlight that strikes its surface. Further, UV light does not adversely affect glass as it does other materials such as plastics. Plastics may warp, but glass does not. However, glass greenhouses are expensive to construct, maintain, and operate. Glass breaks easily, is heavy, and must be handled with care. It does not retain heat well.

Glass is available in several grades and weights, including single-strength, double-strength, heavy-sheet, polished-plate, and heavy-plate glass. For greenhouse glazing, the B grade is most commonly used, even though it is less efficient in light transmittance than the AA and A grades. The superior grades are very expensive. Glass greenhouses generally require extra structural support to bear the weight of the glass. Increased support is offered by closer spacing of sash bars, which then results in more shading. To overcome shading, large and more expensive glass panes may be used (instead of the traditional size of 16 × 18 inches, some panes are 32 × 36 inches). Wider glass panes reduce loss of heat through the junctions between adjacent panes.

Large growers of roses and other holiday plants use glass greenhouses. Glass also has limitations in terms of design of the greenhouse. Four basic styles are used in glass greenhouses—lean-to, even-span, uneven-span, and ridge-and-furrow designs.

Film Plastic (Flexible Plastic Film)

Film-plastic greenhouses have fewer design restrictions than glass greenhouses and are lightweight. They are very inexpensive to construct and are becoming increasingly more popular in use. A double-layer, film-plastic greenhouse can be operated at over 30 percent less than the cost of operating a comparable greenhouse. Another advantage of film-plastic greenhouses is their adaptability to temporary or short-term use. If a controlled environment is required for only a short period for a specific purpose (as is the case in bedding plant production), a film-plastic greenhouse can be quickly constructed and dismantled when not needed. Further, it provides new persons in the horticultural business a less-expensive means of entering the field. Film-plastic greenhouses have disadvantages. They are less durable than glass and may require periodic recovering (e.g., once every three years). The common types of flexible plastic films are described in the following sections.

Polyethylene

The most common but least durable plastic film material is *polyethylene.* This material remains flexible at low temperatures. Polyethylene is permeable to gases such as oxygen and carbon dioxide. Light transmittance through this material is about 5 to 10 percent less than through glass. Ultraviolet light makes plastic material brittle over time, even in the case of the highest-quality, light-resistant, 0.15-millimeter-thick (0.006-inch-thick) plastic. Life expectancy is generally increased by using thicker plastic films or those containing antioxidants and UV inhibitors. These chemical additives reduce the weathering rate of the material. Double sheets of polyethylene inflated with air are widely used for commercial production in places like Texas.

Woven Polyethylene

Woven *polyethylene* is found in greenhouses equipped with retractable roofs (Figure 12–13). This type of roof is made of woven polyethylene, a UV-resistant material capable of preventing water condensation on the inner surface of the roof. It transmits light at the rate of 80 percent of light reaching its surface. High-quality crops are produced under this roof, and the amount of light is closely monitored. The material is quite durable, lasting about five to seven years.

Polyvinyl Fluoride

Another film material, made out of *polyvinyl fluoride,* (Tedlar) is also available. This material is very durable (lasts over ten years), has excellent light transmission properties, and is resistant to UV radiation. It transmits light at a level equivalent to that of glass.

Polyvinyl Chloride

Polyvinyl chloride (pvc) films are more durable than polyethylene films. Unfortunately, vinyl films hold an electrical charge that attracts and holds dust particles over time, thereby reducing light transmittance. Further, it becomes soft on warm days and brittle when temperatures are low. The material transmits long-wavelength infrared radiation at a greatly reduced level, thus reducing heat loss at night.

FIGURE 12–13 Retractable roof greenhouse used for overwintering of nursery crops. The covering material is a woven fabric that is retracted as soon as outdoor conditions allow. The design is strong enough to support some snow and wind load when closed. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

Ethylene–Vinyl Acetate Copolymers

Ethylene–vinyl acetate copolymers are very expensive and thus not widely used as glazing materials. They are durable, of high light diffusion, and less susceptible to weathering than other materials.

Polymethyl Methacrylate (Acrylic)

Acrylic (plexiglass) is an excellent glazing material. It is weather resistant, lighter than glass, and of comparable light transmission with other materials. Structurally, this material consists of plastic to which acrylic has been chemically bonded. It is more expensive than glass. As a glazing material, it has a tendency to turn yellowish after a period.

Earlier greenhouse designs adapted to plastic films included the A-frame and scissor truss film-plastic types. These designs were temporary structures and built on wooden frames. They had to be protected and preserved through regular painting and wood treatments. Some of the chemicals used (e.g., creosote and pentachlorophenol) were discovered to be toxic to plants. A safer wood treatment is copper naphthenate. More durable and modern designs are made of trusses constructed from metal pipes. A popular one is the Quonset greenhouse. It is very durable, inexpensive, and adaptable to *double-layer covering* with film plastic. A dead-air space is created between the two layers by inflating with a squirrel cage fan. The dead-air space has insulating properties and also prolongs the life of the greenhouse.

Since greenhouses are constructed to be as airtight as possible, condensation of moisture occurs in the internal environment. When plastic coverings are used, droplets of moisture often form on their water-repellent surfaces. Although this condensation poses no immediate danger, when the droplets fall on leaves, a disease-promoting condition is created. The water repellency can be eliminated by spraying detergents on the film surface.

Fiberglass-Reinforced Plastic

Fiberglass-reinforced plastic is a semirigid glazing material and can be bent. It is used in constructing Quonset and even-span greenhouses. The light transmission of this material when newly installed is near the quality of glass. However, with time, the light transmittance reduces as a result of etching and accumulation of dust. Fiberglass-reinforced plastic lasts about ten to fifteen years. The fiberglass content disperses light such that its intensity in the greenhouse is more uniform. Greenhouses constructed from this material are also easier to cool than glass greenhouses. They are available in different colors. However, the clear type permits the greatest light transmission, at a level equivalent to that of glass. They are available in flat or corrugated forms. Greenhouses constructed from fiberglass-reinforced plastic and other plastics are more expensive to insure because they are prone to extreme heat or fire damage. These materials are said to be *thermosetting,* or heat setting. However, fire-retardant fiberglass-reinforced material is available.

Rigid Sheet Plastics

Rigid plastics, when cut into panes (resembling glass panes), may be used as glazing materials for greenhouses. The most popular rigid plastic materials are acrylic and polycarbonates and are available as single- and double-layered rolls. Double-layered types are more durable and increase the energy efficiency of greenhouses by about 50 percent over glass greenhouses. Rigid plastic and glass are the most expensive glazing materials in use. Acrylic may last up to twenty-five years, and polycarbonate may last between ten and fifteen years. Because they are relatively less heavy than glass, they require less support and hence are adaptable to wider sash bar spacing. Using fewer sash bars reduces the amount of shading.

Saran Plastic Mesh

Saran-glazed greenhouses are used where the intensity of sunlight is very high. This mesh plastic film is used to provide shade, and hence the greenhouses glazed with this material are sometimes described as saran shade houses. They are used in areas such as Florida, Texas, Hawaii, and California. The material is available in a range of colors, thicknesses, and closeness of weave. These factors affect the degree of shading provided by the material.

12.2.5 SEALING THE GREENHOUSE

A greenhouse is a controlled environment and should be constructed with an "airlock" entrance design. This design incorporates an entrance porch that prevents direct ingress of undesirable wind, soil, insects, and spores into the facility. Greenhouses with this design make it easier to open and close doors when the fans are operating.

12.2.6 GROUND COVER

Greenhouses with bare grounds that expose the native soil are prone to weeds and soil borne pathogens. Some producers line the grounds with gravel. Plastic may be used as flooring material, but concrete flooring is most durable, improving sanitation as well as facilitating the movement of materials in the structure.

12.2.7 COLD FRAMES AND HOTBEDS

Cold frames and **hotbeds** are simple climate-controlling structures for growing plants on a limited scale. The difference between a cold frame and a hotbed is that the latter is simply a cold frame fitted with a heating system. Heat may be supplied by electrical cables beneath the soil or steam run through pipes along the wall. Environmental control is limited to opening and closing the structure or rolling away the covering for aeration and temperature modification (Figure 12–14). The designs are variable. They may either be attached to a regular greenhouse or erected separately. The glazing may be clear plastic or glass. Cold frames are heated by sunlight, which makes their operation very inexpensive. However, their use is limited since environment cannot be controlled. Cold frames may be used for hardening purposes, rooting of hardwood cuttings, raising vegetable seedlings, and limited production of crops such as lettuce, radish, cucumber, and sweet potato. Placing a thermometer inside of a cold frame to monitor the environmental temperature is recommended. For cool-season crops, the structure should be ventilated whenever the temperature reaches 21°C (70°F). Warm-season crops can tolerate a higher temperature, and ventilation is thus needed only when the temperature rises to about 30°C (86°F). Cold frames are not as popular as they once were, largely because greenhouses that provide a broader range of environmental control are used widely.

Cold Frame
An enclosed, unheated covered frame used for growing and protecting young plants in early spring, and for hardening off seedlings.

Hotbed
A bed of soil enclosed in transparent material and heated to provide a warm medium for germination of seeds or rooting of cutting.

12.2.8 CROP TUNNELS

Crop tunnels or high tunnels are structures designed to provides early- and late-season protection of crops for high product quality (see Chapter 20). These structures are about sixteen to twenty-five feet wide and about four to eight feet high. Production of crop like blueberry, strawberry, vegetables, cut flowers, and perennials all experience higher

FIGURE 12–14 A cold frame. *(Source: Peter Anderson © Dorling Kindersley)*

quality of the harvested product when protected from the elements (wind, frost, rain, cold) during production. Strawberries grown under crop tunnels arrive early as well as late on the market for producers to obtain higher prices during these times when demand exceeds supply. Also, the shelf life of fruits is extended by the production.

12.2.9 LOCATING A GREENHOUSE

Greenhouse production is initially capital intensive and hence must be embarked upon only after good planning. The following are important factors for consideration in locating a greenhouse.

Market

The grower must first identify the potential market in terms of its size and distance from the production site.

Accessibility

Greenhouse accessibility is closely related to its potential market. The production site should be readily accessible to the primary customers. If a retail operation is intended, the greenhouse should be located where the general public can readily reach the facility. Certain production operations require that products be delivered promptly to sales outlets. Transportation between greenhouse site and markets should be reliable and convenient. Cut flowers may be able to survive several days of refrigeration with little loss in quality. It is important that supplies for production be delivered on schedule even in inclement weather.

Greenhouses should be readily accessible by a reliable means of transportation because production inputs (including soil mixes, fertilizers, pesticides, and seed) and the harvested produce must be hauled to and from the greenhouse. Locating a greenhouse enterprise near markets significantly reduces operational costs. *Bedding* and *potted plants* are expensive to transport; consequently, these enterprises should be located near primary market outlets, if possible.

Climatic Conditions

The patterns of weather factors including light, rainfall distribution and other precipitation (e.g., snow, ice, and sleet), and winds affect production costs (e.g., heating, cooling, and lighting). High elevations may provide cleaner air but are colder, requiring more heating in the cold season. Establishing a production enterprise for a crop that requires warm conditions in an area that is mostly cold will increase heating costs (unless the area has a great potential market to offset the additional costs).

Topography

Topography affects the drainage of the area. Greenhouses use large amounts of water and must be located on soils that drain freely. Further, it is easier to mechanize operations if the site is flat. It is more difficult to maneuver on slopes than on flat land. Construction costs may not vary, but it is easier to automate a greenhouse built on level ground than one built on a hill.

Utilities

Another factor to consider in locating a greenhouse is the source of water. Greenhouses use large amounts of water for a variety of activities such as watering plants, washing, and maintaining high humidity inside of the facility. If an urban-treated water supply is not accessible, an alternate source of water must be found (e.g., a well). It is critical that the source of water be reliable to provide water year-round. The success of certain production practices depends on the availability of water. The quality of water is also critical, since certain plants are adversely affected by specific pollutants (e.g., fertilizers and pesticides). Pollutants can make water acidic or alkaline. Supplemental light is also required, as is a source of heat for times when the temperature drops below a desirable level. Providing artificial light and heat requires a source of energy. The greenhouse should be located where there is ready access to a reliable and economic energy (fuel) supply.

Labor Supply

The location of a greenhouse should also take into account the kind and availability of labor. Certain chores in the greenhouse are not automated but require some level of skill. Not all greenhouse operations are readily amenable to automation.

Types of Production Enterprises

The type of production enterprise is related to the accessibility factors. Bulky products (e.g., potted plants) are expensive to transport over long distances.

Zoning Laws

Various localities have zoning regulations regarding location of an agricultural enterprise and building codes.

Future Expansion

For a commercial venture, it is advisable to acquire more land than needed immediately. This extra land will allow future expansion to be undertaken as needed.

12.2.10 GREENHOUSE ORIENTATION

The location of a greenhouse is critical to its efficiency. The orientation of the structure has a bearing on the temperature variations experienced within a greenhouse. It is important that tall structures (such as tall trees and buildings) that might cast shade (especially on the south side of the greenhouse) not be in the vicinity. This natural light advantage is diminished when greenhouses are located in areas of intense fog or highly cloudy areas. Shadows are also cast by the frames used for construction. To reduce this occurrence, the ridge of greenhouses in regions above 40 degrees north latitude should be oriented in an east-west direction so that the low angle of winter light has a wider area to enter the house from the side rather than from the end.

12.2.11 GREENHOUSE BENCHES AND BEDS

Greenhouse production occurs either in *ground beds* (in the ground) or on *benches* (raised platforms). The design and layout of these structures should facilitate greenhouse operations and make the most efficient use of space.

Beds and benches in a greenhouse are located so as to allow personnel to freely move around and work and also to move greenhouse equipment such as carts and trolleys. To accommodate equipment, the principal aisles should be about 3 to 4 feet (0.93 to 1.24 meters) wide. Some arrangements are more efficient than others in terms of the efficient use of space. The more usable space, the greater the profits from a greenhouse operation.

In terms of where the planting media and containers are located, three strategies may be adopted in a greenhouse production enterprise.

No Bench

No bench, or floor benching, is the practice in which production takes place directly on the floor of the greenhouse. The floor may be covered with gravel or concrete and should be well draining. It is best to have a gentle slope in the floor so that excess irrigation water drains into a gutter and is carried out of the facility. Gravel covers and porous concrete are prone to weed infestation. Bedding and seasonal plants such as poinsettia are commonly grown on floor benches. Aisle space is created by the way flats or containers are arranged on the floor (Figure 12–15). If done properly, up to about 90 percent of the floor space can be utilized for production.

FIGURE 12–15 A no-bench greenhouse production system showing plants placed directly on the floor. *(Source: George Acquaah)*

FIGURE 12–16 Raised bench. *(Source: George Acquaah)*

Raised Benches

Raised benches are suited to potted plant production. Most greenhouses have raised benches of a wide variety of designs and constructions. Some of them are makeshift and temporary, consisting of brick legs and movable bench tops. The top may be of wood, concrete, or wire mesh and may or may not have side boards (Figure 12–16). Metal benches are most common. Molded plastic is sometimes used to make troughs in which potted plants are grown. This material is also used in the construction of benches for ebb-and-flow irrigation. Notwithstanding the material used, the bench must have a system for draining properly. If wood is used, cedar, redwood, and cypress make good bench materials because they resist decay. Wooden benches may be painted with copper naphthenate preservative to prevent decay. Redwood has natural preservatives that are corrosive to iron and steel; as such, nails and other construction materials that come into contact with this wood should be of different materials such as aluminum or zinc.

The height of the bench above the floor should be such that cultural operations (e.g., pinching, spraying, harvesting, and staking) are facilitated. Width of the bench is also important. It should be narrow (3 to 6 feet or 0.93 to 1.86 meters) enough to permit pots located in the middle rows to be easily reached. Air should be able to move freely around and under the bench, as well as around the pots on the bench.

Ground Benches or Beds

Plants to be grown for several years that will grow tall in the process (e.g., cut flower plants such as roses) are planted in ground beds (Figure 12–17). Ground beds vary in design and construction. Using ground beds can be problematic from the standpoint of disease control. If the ground bed has no real bottom in terms of depth, diseases such as bacterial wilt are hard to control because of the impracticality of thorough pasteurization of the soil to a reasonable depth. To correct this problem, concrete bins may be constructed in the ground to hold the soil and to facilitate periodic pasteurization to control soilborne diseases. These concrete bins have V-shaped bottoms and drain holes for good drainage. They should be about 6 to 12 inches (12.2 to 30.5 centimeters) deep, depending on the plant to be grown. When drainage is poor, drainage tiles may be installed and overlaid with gravel before topping with the root medium. Walkways should be strategically located between beds to allow gardeners easy access to the beds to prepare them, plant the crop, care for it, and harvest the produce. These spaces should be graded so that water flows away from the beds to reduce

FIGURE 12–17 Greenhouse production of lettuce in soil. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

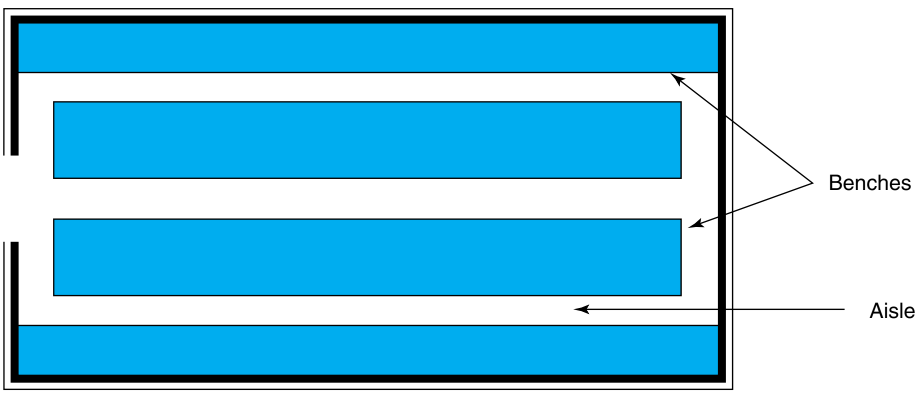

FIGURE 12–18 Longitudinal layout of greenhouse benches.

contamination from pathogens carried on the wheels of carts and wheelbarrows and the shoes of gardeners.

12.2.12 LAYOUT (ARRANGEMENT)

The five types of bench arrangements commonly used in greenhouses are described in the following sections. The layout depends on the crop and the nature of the production enterprise, taking into account row spacing, irrigation type, and structural support systems (e.g., trellises).

Longitudinal Arrangement

In a longitudinal arrangement, beds or benches are constructed to run the full length of the greenhouse in several rows (Figure 12–18). This arrangement is associated with cut flower production. It is easier to conduct mechanized operations with this type of arrangement, which provides for long, uninterrupted production areas. However, moving across the facility is hampered and requires workers to go all of the way to one end of one row to make a turn to the next row.

Cross-Benching

Cross-benching is like the longitudinal arrangement except that the orientation of the benches are not lengthwise with respect to the greenhouse but are arranged crosswise (Figure 12–19). The benches are shorter and aisles numerous. Although the aisle space significantly reduces the usable area of the greenhouse, movement around the greenhouse is easier with this arrangement.

Peninsula Arrangement

The difference between the peninsula arrangement and cross-benching is the presence of a primary central aisle in the former that runs the entire length of the greenhouse. The primary aisle in cross-benching runs along the wall (Figure 12–20).

Movable Benches

Movable benches are especially popular container production enterprises. To maximize the use of space, some greenhouse designs include movable benches and one aisle. When work on one bench is completed, the bench is mechanically moved so that work can be completed on the next bench (Figure 12–21).

Pyramid Bench

A pyramid bench is an arrangement in which benches are placed in tiers. It is an ideal configuration for hanging basket production.

Whether concrete bins or raised benches are used, the layout is important. As previously indicated, aisles must be made to allow equipment to be moved around and to provide working room around the bench while maximizing the use of floor space. In greenhouses designed especially for cut flower production, the ground bed may run the full length of the facility. Designs for nutriculture usually have special designs to accommodate the special equipment they require.

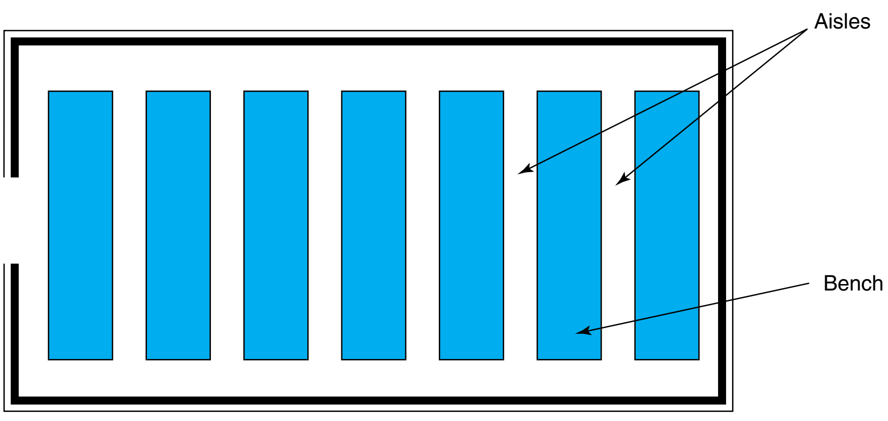

FIGURE 12–19 Cross benching layout of greenhouse benches.

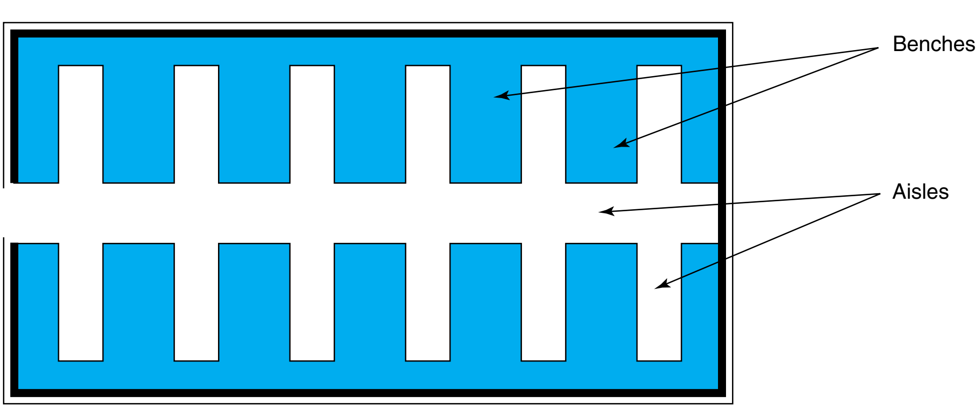

FIGURE 12–20 Peninsula arrangement of greenhouse benches.

FIGURE 12–21 Moving tables allowing for maximized space efficiency of the greenhouse growing area. Note the heating pipes used to provide "bottom heat" to the seedlings grown on the tables. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

12.3 Internal Environmental Control

Greenhouses are controlled-environment facilities because the user is able to adjust at least some of the plant environmental growth factors to meet specific needs. The factors and their control are discussed in the following sections. Modern greenhouse climate control is highly automated. Sensors are installed for measuring factors including temperatures (of the air, water, and growth media), humidity, wind speed, wind direction, solar radiation, carbon dioxide concentration, and rainy conditions. The information is fed into computers with climate control software to regulate the greenhouse conditions to suit the crop or plant cultural activity.

Greenhouse climate is controlled primarily through devices as open motorized windows or vents, ventilations fans, circulations fans, heaters, heating circles cooling pads and misters, thermal shades, sprayers and evaporators, and carbon dioxide generations.

12.3.1 TEMPERATURE

The daytime temperature in greenhouses is usually higher than the nighttime temperature. Room temperature in most greenhouses is maintained at about 13 to 18.5°C (55 to 65°F) (at night) and 18.5 to 27°C (65 to 80°F) higher during the day. Maintaining temperature is the next most expensive operational cost after labor. The greenhouse is essentially a giant solar collector. The sunlight energy that enters the greenhouse during the day is trapped (*greenhouse effect*) and used in heating up the contents of the facility.

How Heat Is Lost

Temperature control is perhaps the major reason for greenhouse use. Greenhouse temperature depends on the heat balance or net energy between the greenhouse system and its surrounding environment. The goals of heating a greenhouse are to provide heat at the appropriate time and in the appropriate amount, distribute it effectively through the facility, and conserve it. The ideal situation is to maintain a stable air temperature in the greenhouse by adding heat at the same rate at which it is lost. Fuel cost is a big contributor to high overhead in greenhouse enterprises. Therefore, heat loss should be minimized. Heat is lost from greenhouses by three ways: *conduction, infiltration,* and *radiation.*

Conducting Heat Loss
Heat loss by transmission through a barrier such as a greenhouse glazing material.

Conduction **Conduction heat loss** is the principal mode of heat loss and occurs through the material used in framing and glazing the greenhouse. Metals conduct heat

Building and Maintaining Greenhouses for Energy Savings

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Rutgers University

Background

Historically the energy consumption of a commercial greenhouse was not necessarily a very high priority item in either facility design or subsequent management. One significant exception was the energy crisis of the 1970's brought on by the oil embargo of 1973, which resulted in shortages of supply and rapidly escalating costs. With the shortages causing significant disruptions there was general consensus that fossil fuels represent a finite supply that must eventually be replaced with sustainable energy resources and that it was prudent for the country to take steps to free itself of dependence on Middle East oil. This stimulated government and industry support of a significant research program on energy conservation and alternative energy sources for commercial greenhouses at several land grant universities. The application of the results of these efforts enabled many greenhouse operations to substantially reduce energy consumption and costs. For those who implemented the most effective steps to reduce fossil fuel use for energy, further significant improvements are much more difficult to discover and implement.

More recently as energy prices climbed past $30 per barrel in the summer of 2004 and later past $60, the cost of energy again renewed concerns of most greenhouse growers. There are some significant differences between the two situations. After the embargo ceased and subsequent price increases moderated there was a long period of relative price stability and net decrease in real energy costs for greenhouse operations that implemented key conservation strategies that were developed. The response of government and industry to substantially fund energy conservation and alternative energy supply research specifically for the greenhouse industry led to significant savings possibilities, but similar responses are not redeveloping recently. The issues that drive recent concerns for energy supply are more complex than earlier. There seems little likelihood of a near term sustained period of price reduction or even price stability. Society in general is now more aware that fossil fuel resources, especially natural gas and oil, are finite and that while some new resources will no doubt be discovered rising global consumption is likely to outstrip the rate of new discoveries. The environmental impact of burning fossil fuels is now much more widely understood than 30 years ago. Political instability in key production regions combined with international terrorism activities substantially compromise supply security regardless of price.

Conservation Developments

The design of the greenhouse structure and the environmental control equipment selected has major impact on the energy consumption of the facility. Beyond that, for any given system there are many factors, beyond alteration of the facility and equipment that the greenhouse manager can implement to optimize energy use for the best management of the crop. There are many good sources of information on energy conservation measures that for any production greenhouse and on the factors to consider in building new facilities or upgrading existing structures or equipment. A comprehensive and extremely useful publication is "Energy Conservation for Commercial Greenhouses," compiled from information developed through an integrated collaborative Northeast Regional

Research program on greenhouse engineering, Bartok, 2001. This publication is available from NRAES, Ithaca, NY, http://www. nraes.org/. There is a website devoted to greenhouse engineering issues maintained by Michigan State University: http://www.hrt.msu.edu/ Energy/ Notebook.htm . There are additional links to information as well as a number of energy related publications posted on the Rutgers Horticultural Engineering website: http://aesop.rutgers.edu/~horteng/.

There are several greenhouse design developments that have significant energy conserving features even if this was not the primary reason for the development. One such is the use of multi-span greenhouses for large facilities rather than a number of single-span units. In exercises 1 and 2 the heat requirements for single and multi-span units can be compared. While the major advantages of the larger unit are the ease of conducting cultural operations and the economy of construction, there is also an energy advantage as the common sidewalls are eliminated reducing the structural area for heat loss. A good rule of thumb is that when the total greenhouse space needed will equal or exceed three single span structures a multi-span unit should be seriously considered.

Another is the development of low-cost plastic film greenhouse structures. The first plastic film covered greenhouses consisted of single layer plastic films fastened with nailers on wooden frames. A significant problem when growing small seedlings was the dripping of condensation, which accumulated on the cold film. To alleviate this problem, a second plastic film layer was added. One early method of construction involved putting on the first layer with a wooden nailer on the rafters that was then also the spacer between the layers. The outer layer was then added with additional nailers to hold this second layer. When recovering, both sets of nailers needed to be removed and then reapplied.

While the initial motivation for double layer covering was to alleviate condensation dripping, it was also noted that the insulating property of the airspace reduced energy consumption by about a third. The breakthrough that made double-layer plastic-film covering practical on a wide scale was the use of a small inflation blower to lightly pressurize air to separate the layers. With this technique it is no longer necessary to add multiple nailers and the glazing need only be fastened around the perimeter of each pair of sheets. The development of this concept and its impact has been recognized by the ASAE Historic Landmark designation given the first structure of this type located on the Rutgers campus. A full discussion of this development and its impact can be found under the ASAE Historic Landmark Dedication link on the home page of the Rutgers University Horticultural Engineering website, http:// aesop.rutgers.edu/~horteng/.

Another effort originally undertaken to solve one problem that evolved into a major energy conservation tool was an undertaking to develop a simple, low-cost, mechanical drive system for black cloth photoperiod control that could be installed by a grower. After installing a system in a glass greenhouse the idea of utilizing the closed curtain for energy savings at night was tried and the first experiment indicated about a fifty percent heat savings. This effort also prepared a good basis for later work on movable curtain systems with materials selected for energy conservation and/or shading. Greenhouse shade and heat retention materials and systems are available for a wide range of solar shading and significant energy savings for night heating are also realized. When a movable curtain system is to be selected for both shading and heat retention the material should be selected for its shading property first. In some cases it is desirable to install more than one curtain for finer control of shading and cumulative heat savings. Exercise 5 can be done for several choices of commercially available curtain materials and the relative energy savings compared.

To further understand the potential of moving curtain systems for energy conservation, a series of experiments were carried out in a small research greenhouse and an environmental control chamber (Simpkins et al., 1976). The energy savings of a curtain system in a greenhouse are due both to the insulating value of a trapped airspace between the curtain and the glazing and the ability of the curtain to block outgoing thermal radiation.

Since glass is essentially opaque to thermal radiation, the major contribution to energy savings of a curtain in a single glazed glass greenhouse is the reduction of conductive and convective heat loss by the creation of a dead air space. Radiative heat loss from a glass greenhouse is a two-step process, from the crop to the glazing and then from the glazing to the external environment.

Double-layer plastic-film covering already has the advantage of an enclosed air space with additional energy savings achieved by adding a second dead air space by installing the curtain. Pure polyethylene is highly transparent to thermal radiation so most radiative heat loss is directly from the crop canopy through the covering to the external environment. For this reason the thermal emmisivity of a curtain material used for energy savings in a polyethylene covered greenhouse is very important. It was found that aluminized materials with a very low thermal emmisivity are preferable for reducing the radiative component of the heat loss. For all curtain materials it was found important to achieve good closure at the edges and ends to prevent air circulation around the curtain, which would reduce the insulating value of the trapped air space.

The energy conserving potential of a number of different curtain materials were evaluated during the 1970's at several universities and other institutions. When employed in glass greenhouses a major benefit of the curtain is the creation of a dead air space between the curtain and the glazing. Curtain materials with relatively low thermal emissivity, such as aluminized materials, will transmit less energy to the glass by radiation. Glass itself absorbs thermal radiation contributing significantly to reduction in thermal radiation heat loss relative to pure polyethylene, which has a high transmission of thermal radiation. In the case of double layer polyethylene greenhouses there is already a dead air space so the savings due to adding another such space with the curtain is less significant than in a single glazed greenhouse. However, as pure polyethylene is highly transmisive of thermal radiation the radiative properties of the curtain are more significant than for curtain materials installed under glass. Aluminized materials with low thermal emissivity are particularly effective at reducing heat loss from the crop to the sky by radiation.

Initially there were no materials available that had been specifically designed for greenhouse energy conservation so trials were based primarily on materials developed for other uses and adapted to this application. Radiation heat loss is significantly greater under clear skies than cloudy or rainy conditions so the actual heat savings will vary with weather conditions. The average savings for the best of the materials tested was over half for both types of glazing systems, with the major benefit being the first dead air space for single glazed structures and the major benefit the radiative property of the curtain material for double polyethylene structures. While almost none of these early materials tested are in current use, in later years other materials have been specifically designed for greenhouse applications.

In the early 1980's research was undertaken at Rutgers University on the energy conserving potential of adding an infrared (IR) absorbing material to polyethylene greenhouse covering to overcome the problem of high radiation loss through such covers. Earlier research had shown the increased significance of radiation loss in polyethylene-covered greenhouses relative to glass. The purpose of this research program was first to document and confirm the energy savings potential of and IR additive, second to determine what significant changes in plant growth could be expected, and finally to better understand the details of heat loss through double layer polyethylene covering with and without the IR inhibition feature, (Simpkins et al., 1984).

Four experimental greenhouses were constructed and fully instrumented so that glazing systems of IR film, non-IR film and combinations could be compared. Instrumentation included a full weather station and instruments to measure total energy transmission, PAR transmission, net heat radiation both from the plant canopy to the glazing and from the glazing to the sky as well as infrared thermometry to measure plant surface temperature and numerous thermocouple temperature sensors. An important aspect of this complete instrumentation system was the ability to constantly evaluate heat loss from the greenhouses both in terms of total heat loss and the component of heat loss that was radiation under all weather conditions. Earlier work on measuring heat loss from greenhouses equipped with a variety of curtain insulation systems had demonstrated the significant variation in transfer rates under different weather conditions. From this work it was possible to develop a quantitative relationship between the heat loss coefficient of each covering system and the weather conditions as defined by wind speed and sky clearness index. It was found that the sky clearness index has a strong influence on radiative heat loss from the greenhouse that is substantially reduced by the IR inhibitor.

In addition to determining the heat loss characteristics of the different films and their combinations, light transmission and changes in transmission were evaluated. PAR light transmission of both types of film were generally comparable with the non-IR film having slightly greater transmission initially and both films loosing some transmission over time due to a combination of dirt build up and film darkening. Both film darkening and reduction in light transmission due to dirt accumulation were measured at the end of the test period. As the IR film did not darken as much or accumulate as much dirt over time it had slightly greater light transmission in the second year of use. Another effect of the IR inhibitor, which is generally accepted as significant for improved plant production, is that the transmitted light is much more diffuse than is the case for the non-IR film. The heat savings in the series of tests varied from about 25% to 40% depending upon weather conditions. While the specific film developed and tested in the early 1980's is no longer commercially available, IR inhibited films are in widespread use with similar energy savings characteristics according to manufacturers. An important aspect of both IR inhibited plastic films and internal curtain systems is that in addition to the energy savings, the reduction in heat loss by radiation results in significant increases in plant tissue temperatures relative to the greenhouse air which can result in slightly lower thermostat settings for air temperature resulting in additional energy savings.

Another research activity of the late 1960's, not initially regarded has having energy savings consequences, was focused on improving the watering systems for tomato production in trough culture. While doing this work, several attempts were made to also increase the temperature of the root zone by watering with warm water but it was found that within less than an hour, with evaporation and other heat loss, soil temperature had returned to its initial condition. Therefore several techniques were tried to keep the soil warm, including circulating water in plastic tubes under the beds, which served to keep the soil warmer and did improve growth. This observation led to an increasing interest in using floor-heating systems to augment traditional overhead heating systems and to reduce the difference between colder root zone and warmer overhead air temperatures for crops grown on the floor. Without soil heating, it is often necessary to overheat the greenhouse air to achieve target soil temperatures. An independently controlled soil heating system has the potential to reduce the total energy requirement by reducing the air temperature and thus the heat loss from the greenhouse. More importantly, the ability to have somewhat independent control of soil and air temperature enables the grower to find the right combination of soil and air temperatures for a given crop and at a given stage of development. In general, the aim of the environmental control engineer should be to provide environmental control tools to the grower, and clearly independent control of soil and air temperature give more management opportunities to the grower.

A number of techniques have been developed for root zone heating in greenhouses and during research at Rutgers University heat transfer coefficients for many have been measured and used to guide system design (Roberts and Mears, 1980). More detailed information on the research and guidance on system design is available on the Horticultural Engineering web site and in the publication NRAES-3. Early research focused on designs incorporating plastic or rubber tubing in porous concrete floors. Porous concrete, produced with aggregate and cement but no sand, provides a solid working surface and good drainage for pots and flats placed directly on the floor. Both small diameter tubing and 3/4 inch plastic pipe were initially studied to determine the uniformity of floor surface temperature and heat transfer rate as determined by the spacing of the pipes within the floor and the arrangement and moisture condition of the pots or flats on the floor.

Through the extension program, a large number of commercial installations of floor heating systems were designed for growers to install on their own throughout the world. In addition some bench top systems were designed utilizing 1/2 or 3/4 inch plastic tubing, and smaller diameter tubing systems provided by commercial suppliers have come into widespread use. In all cases it is important to design the system so that the floor or bench surface is heated uniformly so the crop will be uniform. An important characteristic of root zone heating systems is the large heat storage capacity. Soil temperature will only change slowly in response to changes in the aerial environment or changes in the temperature of the circulating water that is the heat source. This means that, unlike air temperature, root zone temperatures cannot be programmed to change significantly except over long time periods.

To consider the implications of the energy conservation aspects of the various greenhouse design choices discussed above consider the energy requirements representative designs of commercial greenhouses. In Table 1 below the annual heat requirement for an acre of growing space at temperatures ranging from 50 to 70°F have been calculated based on a 10 year composite hourly weather data base for the Philadelphia International Airport. Similar calculations could be prepared for locations with different weather patterns and compared with commercial experience. The heat transfer coefficients for glass, polyethylene and IR inhibited polyethylene used in this table are based on values presented in NRAES-3 and the glass plus curtain figures are based on tests done in The Netherlands for modern curtain materials. The coefficients for plain and IR inhibited polyethylene with modern curtain materials are estimated from the others. These figures are useful for comparative purposes but it is important to note that specific building design, location and exposure to wind, installation of glazing and curtain systems, heating system design and other factors all affect actual fuel consumption.

Single span greenhouses would require more fuel than multi-span gutter-connected units for all temperatures as seen by comparing the first two rows. For example, for greenhouses in reasonably good repair running at 65°F, an acre of single span glass houses could require about 123,000 Therms while a gutter-connected block of the same size would need about 80,000 Therms. For the calculations in Table 1 the wall heights were all assumed at 12 feet, though even higher wall and gutter heights are becoming increasingly popular. Reducing wall height would have some significant savings for the single span units but not for the gutter connected designs. A significant advantage of a gutter connected greenhouse for large areas is that with the elimination of many side walls the heat loss from the walls is minimized relative to that through the roof and relative to the floor growing area. Increased height is advantageous in that space is available for mechanical systems, curtain systems, lighting and automation. Also research and experience has shown that height promotes uniformity of environmental conditions, particularly in cooling.

Continuing with the comparison at 65°F, an acre block of gutter-connected double-layer polyethylene would only need 50,000 Therms and adding a good energy conserving curtain system could reduce this requirement to 37,000 Therms. The development of IR

TABLE 1 Annual per acre heat requirement in Therms

Greenhouse Temperature °F →	50	55	60	65	70
Small single span glass units	48,582	69,074	93,330	123,041	161,823
Large gutter connected glass	30,393	42,662	59,014	80,490	107,342
Gutter con. plain polyethylene	18,089	25,949	36,529	49,949	66,097
Gutter con. IR poly	11,701	16,946	24,025	32,915	43,683
Gutter con. poly + curtain	13,204	19,216	27,231	37,353	49,484
Gutter con. IR poly + curtain	8,995	12,993	18,252	24,897	33,027
Gutter con. Glass + curtain	13,037	18,980	26,911	36,884	48,928

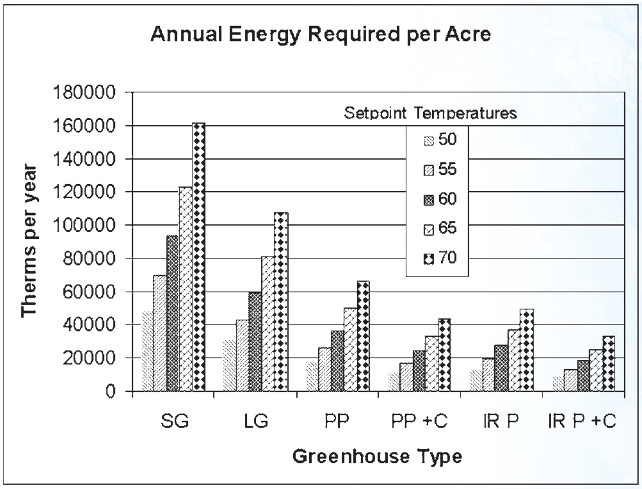


FIGURE 1 Annual energy required per acre by greenhouse type. *(Source: A.J. Both and D.R. Mears)*

inhibited film reduces heat requirements significantly relative to uninhibited film and the IR additive reduces the 50,000 Therm heat requirement to about 33,000. Combining the IR feature with the curtain system provides a further reduction to 25,000 Therms. Thus the grower with an acre under IR inhibited poly with a modern curtain system has almost a 5:1 advantage on his heat bill relative to a competitor in single span glass units with no curtain.

Of course operating temperature has a significant impact on all greenhouse designs, particularly in the milder months of spring and fall. Those greenhouses kept at warmer temperatures would need more heat than those running cooler as shown by comparing columns in Table 1 for all designs. Any management strategy that allows for temperature reduction some or all of the time is helpful. It is possible and even beneficial for many crops to lower air temperatures, providing the soil can be kept warm. Thus with a soil heating system significant energy savings can be achieved. For example, if a floor heating system were added that would enable the air temperature in the IR polyethylene with curtain greenhouse to be reduced 5°F to 60°F the heat requirement would be further reduced to 18,000 Therms per acre per year and if the same crop could do well with warm soil and only 55°F air that drops to only 13,000 Therms. These approximate estimations of annual energy consumption for a range of structural designs, glazing options, use of curtains and floor heating demonstrate the tremendous differences that there can be in fuel bills from one situation to the next.

The results for the first six greenhouse types tabulated above are plotted in the bar graph in Figure 1 for easy comparison. In a survey of greenhouse energy use conducted by Ohio State University in 1979, it was found that the fuel consumption of glass greenhouses in Ohio averaged the equivalent of about 100,000 gallons of fuel oil per acre of greenhouse, (Short et al., 1979), indicated by the line on the bar chart at 100,000 therms. With typical heating system efficiencies at the time, a gallon of fuel oil consumed would result in about 100,000 BTU, (1 Therm), delivered to the greenhouse. It should be noted that many of those greenhouses were single span glass greenhouses and the figures would include the energy consumption of such houses that were not in good repair and would have higher fuel consumption than any of the illustrations. It should be noted that even as of the writing of this section one can tour significant numbers of commercial greenhouses where the state of repair and maintenance will be such that actual fuel consumption will be much greater than this 1970's average.

Energy Supply Alternatives to Fossil Fuels

One alternative to fossil fuels for greenhouse heating is non-fossil fuel, primarily biomass of one form or another. Wood in various forms has provided an alternative fuel source for some greenhouse operations that have been able to secure a reliable supply and develop systems for handling the solid fuel. Various pellet stoves and furnaces have come on the market capable of burning wood pellets and/or shelled corn. Pelletizing biomass facilitates automation of the feeding of the fuel to the furnace and these systems are more fully described on the MSU website. A large greenhouse operation in Ireland has been heated for a long time on peat. Methane produced from biogas generators or landfills. The concept of using landfill gas was the basis of a research project on cogeneration of heat and electricity for greenhouse operations, (Ekholt et al, 1983) that later became the basis for design of a prototype facility at a county landfill in New Jersey, (ref something on the Burlington facility, perhaps just the website?). A large commercial facility using landfill gas for cogeneration and greenhouse heating has been developed in Vancouver, Canada, (http://www.cityfarmer.org/LandfillGas.html).

Another energy source to consider is electricity, which would not have been considered at all in the past due to its relatively high cost. However, as the global energy supply markets have been changing and all costs going up, in most areas electric rates have risen far less than natural gas or oil. This trend can be expected to continue for some time and as a result there are areas where electric rates are competitive or below gas or oil on the basis of energy delivered. A major factor in this shifting of relative costs is the variety of energy sources used for electricity generation including nuclear, hydro, relatively low cost coal and hopefully increasing reliance on renewable resources. Electrical generation depends on oil for only about 3% of capacity, (Woolsey, 2006).

Alternative Energy Strategies

At the time of the 1973 oil embargo, a paper was written to advance the idea of using power plant waste heat as an energy source for greenhouse operations, (Mears et al., 1974). The major ideas presented included the concept of somehow establishing a floating greenhouse floor over a pond of warm water to warm both the soil and the greenhouse air. Another idea presented was that of spraying the warm water between the double layers of polyethylene glazing creating a warm barrier between the internal and external environments. Some work was done on this latter concept including running the water during the day when it was found to intercept about 15% of the incoming energy without significantly reducing visible light. This is because water does absorb infrared radiation to a high degree and a significant portion of incoming solar radiation is in the infrared region. Of the two concepts presented, the floor heating idea seemed the most promising and became the focus of attention. Another idea considered in this paper was that of using solar energy for commercial greenhouse.

In response to the energy crisis resulting from the 1973 oil embargo, the USDA funded a research program to utilize solar energy for the heating of greenhouses and this was followed by a DOE funded commercial demonstration program. Utilizing these resources, a full system was developed incorporating the movable shade/heat retention curtains in double-layer plastic-film covered greenhouses with a system to store warm water heated by low-cost plastic-film solar collectors under the greenhouse floor. The floor heating system developed for solar energy heating systems and later adapted for cogeneration and power plant reject heat applications is the storage floor. A plastic liner is put down, usually over a thin layer of closed cell insulation to protect the liner from punctures. The liner is filled with approximately 9 inches of gravel that can be flooded with water and capped with a concrete floor. In solar systems, the water is pumped through the collectors in daytime and the heat is released during the night. Since the heat storage capacity of the gravel/water combination is so large, the temperature rise during the day and drop at night is modest. As the entire floor surface is the heat delivery system the water in the floor is only warm and the floor does not significantly contribute heat to the greenhouse during the day. When used with either a cogeneration unit or industrial waste heat source, the heat can be added to the floor storage whenever available.

This system was demonstrated in a 58,000 square foot section of greenhouse at Kube Pak Garden Plants, Inc. in Allentown NJ. Experience with this complete system quickly showed that the major benefits, on a commercial scale, to both energy conservation and improved plant growth, were the curtain system and the floor heating. While the solar collectors did make a significant contribution to the savings of fossil fuel, the major energy savings were derived from the curtains and floor heating for those crops grown on warm floors with reduced air temperatures. As noted earlier, curtain insulation systems and root zone heating are widely applied in commercial greenhouses but use of solar collectors as a source of warm water for root zone heating has not been widely adopted. As the cost of gas and oil continue to escalate the economics of utilizing solar collectors for this type of application are likely to improve. A portion of the 58,000 square feet of the first crop of fall Poinsettias grown on the warm floor under the energy saving curtain are shown in Figure 2. Figure 3 illustrates the low cost solar collectors used to warm the water in the floor. The energy savings due to the greenhouse construction, warm floor, energy saving curtain and solar collectors are documented in Figure 4.

Partly as a result of the technical success of the large commercial solar energy demonstration project, interest in the use of industrial waste heat led to the design and construction of a 3-acre commercial greenhouse facility in 1980. The performance of this first block is fully described by Manning et al., (1983). Like the solar demonstration project, the first and most important aspects were to design an energy efficient multi-span greenhouse with insulating curtains and a floor heating system. The first floor heating system incorporated the flooded floor for heat storage capacity as well as maximum heat transfer capability with warm water from the power station circulating through plastic pipes on one foot centers embedded in the under floor gravel. Waste heat could also be circulated through finned pipe in the greenhouse and there was a coal fired back-up system that could be used to provide additional heat in the coldest weather. During the first years of operation there was only connection to one of two cooling towers at the power plant seen in Figure 5, so the back-up system had to be used when that unit was

FIGURE 2 First crop of fall Poinsettias. *(Source: A.J. Both and D.R. Mears)*

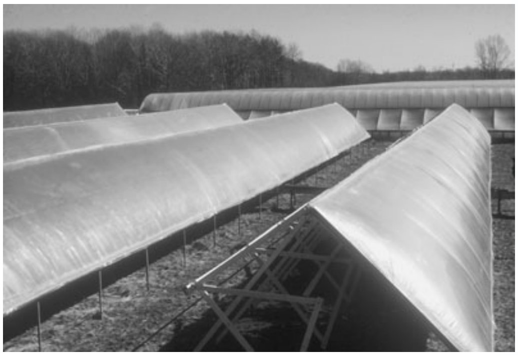


FIGURE 3 Low cost solar collectors. *(Source: A.J. Both and D.R. Mears)*

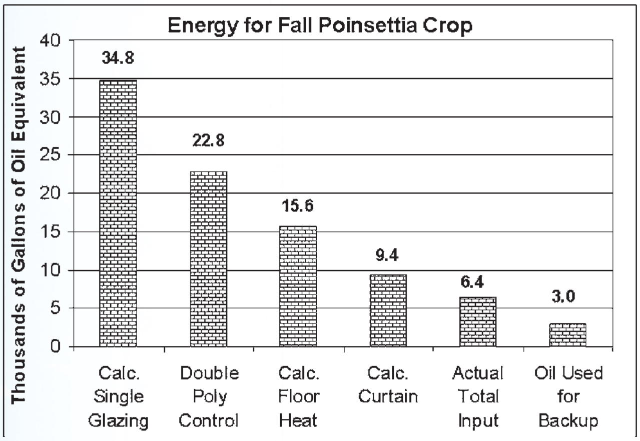


FIGURE 4 Energy savings for Poinsettia crops. *(Source: A.J. Both and D.R. Mears)*

FIGURE 5 Cooling towers at power plant. *(Source: A.J. Both and D.R. Mears)*

not operating. When operating, the power plant provided about 95% of the greenhouse heat requirements.

In subsequent years additional acreage was built, some with the storage floor concept, some with plastic pipe circulating the warm water in porous concrete floors and some utilizing solid concrete floors with ebb and flood irrigation. Later units were able to utilize newly developed forced air heat exchangers specifically designed for larger volumes of lower temperature water to replace the finned pipe for air heating. By 1993 the greenhouse range at this site had grown to over 15 acres and in that winter an unusual snowstorm caused significant structural damage. The reconstruction provided the opportunity for significant redesign of some of the waste heat delivery systems utilizing knowledge gained in evaluating system performance over the years. The redesign significantly improved the effectiveness of utilizing the waste heat resource and the performance of the heating system (Mears and Manning, 1996).

The principles of utilizing both solar energy and industrial waste heat have been demonstrated on large commercial facilities and the technology can be applied at additional facilities. For solar thermal collectors to achieve greater utilization the key issues are the economics of the application, the availability of space for the collectors and the smooth integration of the management of the solar aspects with the greenhouse operating systems and management. For the utilization of industrial waste heat site specific issues include the match between the characteristics of the available heat in terms of temperature and quantity and the needs of the greenhouse as well as the logistical and business aspects of tapping into the resource. It has been recognized that greenhouse operations and industrial activities such as electric power generation are significantly different businesses and the importance of establishing good communications and relationships for a specific project cannot be overlooked.

While the use of solar energy and industrial waste heat has been demonstrated as practical on a commercial scale there are a number of other opportunities yet to be tried on such a scale. Several of these have been modeled in computer simulations to analyze

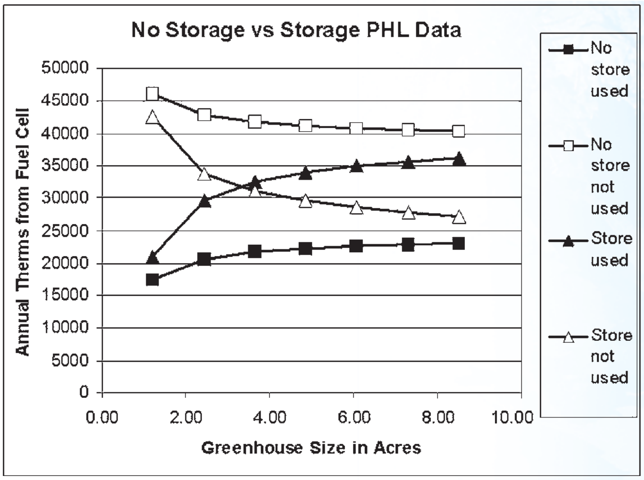


FIGURE 6 Amounts of waste energy utilized in various size greenhouses. *(Source: A.J. Both and D.R. Mears)*

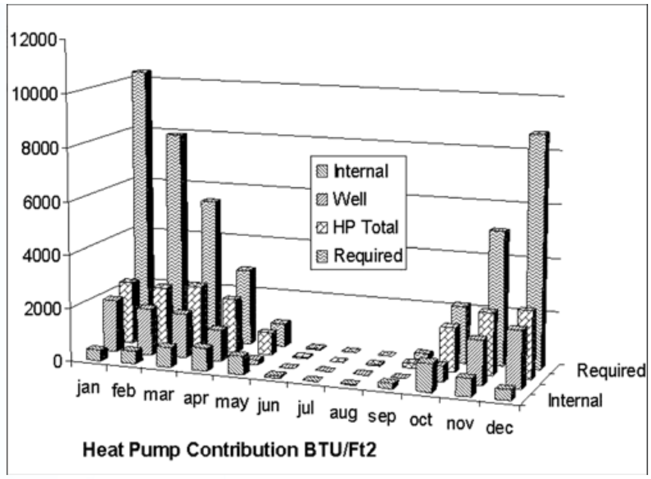
technical feasibility and identify key design relationships, (Ekholt et al, 1983 and Both et al, 2007). Using performance data from a small cogeneration unit designed to operate on landfill gas the first study was done to compare the relative effectiveness of floors with and without the flooded storage. It was found that the larger storage capacity provided more management options for both the sizing of the cogeneration unit relative to the electrical load of the greenhouse and the periods of operation of the unit to realize optimum economics. The later study investigated alternative warm water storage systems and capacities for more flexibility in matching specific greenhouse operations.

Additional concepts modeled include the use of an industrial scale fuel cell designed to operate on natural gas. With sufficient storage it was found that matching such a unit to an appropriately sized greenhouse will enable a half or more of the total waste heat put out by the unit over a year to be utilized in the greenhouse. In addition there is the opportunity to capture the carbon dioxide that is produced by the unit as it first converts methane to pure hydrogen for the fuel cell exhausting the carbon component as carbon dioxide. The key barrier to economic application of such a unit remains high initial cost. Figure 6 illustrates the amounts of the waste energy generated by a 200 kW fuel cell that can be utilized in various size greenhouses. Having significant capacity to store heat enables the greenhouse to use the full daily output when heat is only needed at night. The weather database used for the calculations in the figure is a composite constructed from ten years of records at the Philadelphia International Airport.

Another concept investigated is the use of a heat pump for environmental control in a greenhouse. With the continuing rise in the cost of gas and oil relative to electricity noted previously the use of a heat pump, which may generate three to six times the output relative to electricity input, would become economically competitive as the operating cost savings amortize the initial investment. An efficient system can incorporate a water-to-water heat pump using groundwater as a source for heating and/or a sink for cooling. As the equipment is relatively expensive there is significant economic advantage in using energy thermal storage so a smaller unit can run day and night with the heat generated during the day available for night heating. Such a system should be designed to meet only base load heat requirements with a lower cost backup system on gas or oil utilized for peak requirements.

As heat pumps provide cooling capacity as well as heating another mode of operation can be considered in which the heat pump provides early stage cooling to the greenhouse. With storage for cool and warm water the heat pump can cool the greenhouse during the day in fall, winter and spring storing the heat for use at night. A significant advantage of such an approach is that the greenhouse may be kept closed longer during periods when only early stage ventilation is needed and ventilation can be reduced under hotter conditions thereby extending the time that carbon dioxide enrichment can be economically employed. Figure 7 illustrates the contributions to the heat requirements that are predicted for various months for a proposed system cooling the greenhouse when needed but drawing on a well at other times to maximize its utilization. The large, energy efficient greenhouse was projected to

FIGURE 7 Contributions to the heat requirements predicted for various months. *(Source: A.J. Both and D.R. Mears)*



require 43,580 BTU/ft^2 per year and the heat pump with a heating capacity of 3.4 BTU/(hr*ft^2) would collect 5,509 BTU/ft^2 per year when doing internal cooling and another 11,221 BTU/ft^2 per year from a well for a total contribution of 38% of the annual requirement. The cooling capacity corresponds to the requirement for first stage cooling.

Summary

There are substantial differences in the energy requirements of commercial greenhouses determined in large part by the design of the facility but also influenced by the maintenance and management strategies. These differences are so significant that examples can be found in commercial practice where energy consumption per unit growing area will be at least ten times as great as could be achieved. There are excellent sources of information with specific application to various types of greenhouse operations and increasingly this information can be found on websites and some of these will be periodically updated as new information becomes available.

Beyond the application of the best design and management practices and the consistent following of maintenance procedures there are also alternatives to fossil fuel consumption that can be pursued and it can be expected that practical examples will increase as new ideas are further refined and developed and the relative price of natural gas and oil continue to escalate. There have been many practical demonstrations of systems burning alternative fuels whose economics depend on the facility designed to take advantage of the fuel and its availability and cost. Beyond that further development of alternative energy systems can be expected. Several potential systems mentioned above have been analyzed well enough to show progress and hopefully will be evaluated on a commercial scale.

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faster than glass, and glass conducts heat faster than plastic. Heat loss is related to surface area. Thus, a corrugated (corrugation gives it more surface area) fiberglass-reinforced plastic greenhouse loses more heat than a flat-plate plastic one. If a glazing material loses heat rapidly, it is more expensive to heat a greenhouse constructed out of it. An estimated 40 percent of savings on heating costs may be realized with a properly constructed double-layered plastic covering because of the insulating property of dead-air space.

Infiltration Greenhouse heat is lost through cracks and holes that occur in the structure. This mode of heat loss is called *infiltration*. Cracks occur in places such as the area around closed doors and improperly closed vents. Anytime doors are opened, fresh cool air enters the greenhouse. This influx of air increases heating costs. Older and poorly maintained greenhouses often have air leakage problems.

Radiation Heat can also be lost from a greenhouse through radiation. **Radiant heat loss** is minimal and occurs as heat energy is lost from warmer objects to colder objects. Polyethylene covering can lose large amounts of heat through radiation, whereas glass and fiberglass-reinforced plastic lose virtually no energy to radiation. Water on the plastic covering can reduce this energy loss in polyethylene greenhouses.

Radiant Heat Loss
The radiations of heat from a warm body, such as a plant, to a cooler body, such as the glazing material of a greenhouse.

Heating a Greenhouse

Types of Fuel Three types of fuels are commonly used to heat greenhouses. The most popular is *natural gas*. It is relatively inexpensive, burns clean, and is delivered to the facility directly via pipes in most cases, thus eliminating storage and delivery costs. Its heat value is about 1,000 Btu per cubic foot. (One Btu is the amount of heat required to raise the temperature of one pound of water by 1°F.) *Fuel oil* is second in popularity to natural gas. It is often used as a backup fuel where natural gas is used. A grade 2 oil has about 140,000 Btu per gallon. Apart from the storage required when fuel oil is used, its viscosity is affected by temperature. As such, oil does not flow properly at low temperatures, the time when heat is needed the most. Further, it has undesirable ash as a product of combustion. The third and least preferred heating fuel is *coal*. It produces considerable pollution when

FIGURE 12–22 Dual-fuel boiler system. This boiler can be operated on fuel oil or natural gas depending on availability and pricing of the different fuels. (*Source*: Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

burned. The ash produced from burning coal poses a disposal problem. If the coal has a high sulfur content, pollution is an even greater problem, requiring additional equipment to be installed in some cases to reduce air pollution. Because exhaust fumes are toxic to greenhouse plants, it is critical that during greenhouse construction the exhaust stack be located downstream of the wind. Such a location ensures that fumes have little chance of polluting the greenhouse environment.

In choosing a fuel type, one should consider the following:

1. *Availability.* The source should be readily available year-round.
2. *Delivery or transportation.* The cost for delivery of the fuel is important. If gas is used, will it be delivered by truck or piped to the site?
3. *Storage.* If gas or fossil fuel is selected, there must be a storage facility to hold it while in use.
4. *Special equipment needs.* Gas must be stored under pressure in a container.

Heating Systems

Greenhouse heat is circulated through several different kinds of media.

Hot Water Heating Systems The fuels described earlier are used to heat water, in a boiler (Figure 12–22) which becomes the medium through which heat is circulated throughout the greenhouse. Hot water systems are adapted for use in small greenhouses. The temperature of water may be varied as needed. The disadvantage of this system is that an elaborate network of pipes is usually needed to carry the hot water from a boiler throughout the facility. Further, if a gravity flow return system is installed, gravity causes cold water to flow back into the boiler, thus reducing its efficiency. Modern systems utilize forced-water circulation. Apart from being more expensive to heat and maintain a desired temperature, its heat value is lower than that of steam. Further, hot water is not amenable to use in pasteurization. The system is adapted to small greenhouses because it is difficult to transfer water over long distances without losing heat (temperature drops over long distances).

Steam Heating Systems Steam can be heated to a higher temperature (100 to 101.7°C or 212 to 215°F) than hot water. Smaller pipes are needed to transport steam over long distances and hence can be efficiently used in large greenhouses. In large greenhouses, the steam pressure at the boiler may be as high as 120 psi (pounds per square inch). Even though steam can be transported over long distances, it condenses in the pipes; thus, provision must be made to drain and recirculate the water for reheating. Steam is very efficient for pasteurization.

Radiant Energy Heating System

INFRARED RADIANT HEATER Heating a greenhouse by infrared radiation is very economical. Reductions in fuel bills of about 30 to 50 percent have been reported. Heat is not conducted through any medium but transmitted directly to plants (or other objects) without even warming the surrounding air. As such, while plants receive the desired temperature, the general greenhouse atmosphere may be several degrees colder than would be the case if hot water or steam were used. Even though infrared heaters are highly efficient, the equipment or sources of the radiation must be located directly above the plant or object to be warmed. Failure to provide for such placement will result in **cold spots** (pockets of low temperature) in the facility. Further, as plants grow bigger, they tend to block the radiation from reaching the soil, leaving it cold.

Cold Spots
Pockets of low temperature in an enclosed area caused by nonuniform distribution of heat.

SOLAR RADIATION SYSTEM Like infrared radiation, solar heaters are nonpolluting. The initial cost of solar collectors is high, but they are cost effective once installed. A major disadvantage with solar heating is its weather dependency. Clouds limit the effectiveness of this system.

COAL The third and least preferred heating fuel is coal. It produces considerable pollution when burned. The ash produced from burning poses a disposal problem. If coal has a high sulfur content, pollution is even greater, and laws may require that additional equipment be installed to reduce air pollution. Since exhaust fumes are toxic to greenhouse plants, it is critical that the smoke stack be located downstream of the wind, preventing the fumes from polluting the greenhouse environment.

Design of Heat Distribution System

Heat is provided in a greenhouse by using a *heater.* In terms of the nature of the source of heat, a heater may be *localized* or *centralized.*

Localized Heaters The various designs of localized heating systems are described in the following sections.

UNIT HEATERS Unit heaters are also called *forced-air heaters.* They burn fuel or circulate hot water or steam in a chamber and then depend on a fan to blow on the hot surface to spread the warm air either vertically or horizontally through the greenhouse (Figure 12–23). The more popular models expel heated air horizontally and are called *horizontal units* (as opposed to *vertical units,* which are suspended from above). Because such heaters use oxygen for combustion, there is a potential danger in their use in airtight greenhouses. All of the available oxygen could be used up such that if the burner has been on for a long time (e.g., overnight), carbon monoxide could accumulate in the greenhouse to dangerous levels and be life threatening to anyone entering the building. Further, in more airtight greenhouses such as those with plastic covering, oxygen shortage has been blamed

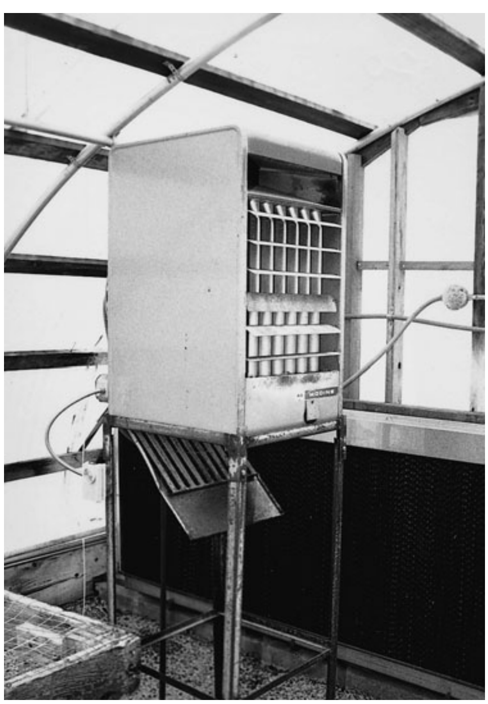

FIGURE 12–23 A forced-air unit heating system. *(Source: George Acquaah)*

for burners going out during the night. To avoid these situations, greenhouses that use unit heaters are designed to have a 1 square inch (6.5 square centimeter) opening in the structure to let fresh air in at all times. Unit heaters are readily amenable to automation. All heaters that use open flames to burn fuel require adequate ventilation through a chimney pipe vented outside of the greenhouse. These units are also called *venting heaters.*

Convection Heaters Convection heaters are another class of localized heaters that, like unit heaters, burn a variety of fuels in a fire box. Heat is distributed by convection current, a natural process. The pattern of airflow depends on the location and arrangement of heaters. Generally, in convection current flow, warm air rises and cold air drops. These heaters are suitable for small-scale use and not readily amenable to automation; however, they are relatively inexpensive. Whenever fuel is burned, it is critical that the exhaust system be effective and efficient in removing all products of combustion from the greenhouse. Such materials include products of incomplete combustion such as ethylene gas, which is harmful to plants. Other exhaust products include sulfur dioxide gas, which when dissolved in water forms corrosive sulfuric acid that scorches plants on contact.

Radiant Heaters Radiant heaters do not burn fuel. They do not warm greenhouse air directly but depend on radiant energy (infrared) to warm objects in their path, which in turn warm the air in their vicinity. Radiant heaters, which are low-energy heaters, are reported to be over 30 percent more efficient than other sources of greenhouse heat. Since air is not heated directly as in conventional systems, the air temperature in a greenhouse heated by this source may be as much as 4°C (7°F) cooler than that in conventionally heated environments. Problems with condensation on surfaces, a common occurrence under warm air conditions, are reduced and subsequently the incidence of diseases associated with condensation is also lowered when using radiant heaters. Further, the greenhouse environment is heated uniformly with little heat stratification. When using radiant heaters, the fans often installed to aid in air circulation under conventional heating systems should not be used. These fans tend to cool the plants and other surfaces and move the heated air around them away. Since the air temperature is lower, the temperature differential between the outside and inside air is lower, resulting in less heat loss. Radiant heaters consume about 75 percent less energy than conventional heaters.

When heaters that combust fuels are used, the potential for injury to people and plants from the pollutants they release into the air is real and must be monitored. In addition to carbon monoxide, products of incomplete combustion such as ethylene can injure sensitive plants such as chrysanthemum. Fuel impurities such as sulfur are burned and converted to sulfur dioxide, which, when dissolved in moisture, produces the corrosive sulfuric acid that burns leaves.

Centralized Heaters Centralized heating systems require a greater investment than localized heaters and are economical for large operations. A boiler produces the heat source, which boils the water that is pumped through pipes and other accessories laid through the greenhouse (e.g., mounted on curtain walls). Pipes may also be located under benches or hung over the plants from the roof. Heat is lost through the plumbing and other parts of the boiler. To increase the surface area for heating, square metal fins may be attached to the pipes in series. Centralized heaters are more efficient than localized heaters. The boiler should be located in the service building, where it is dryer, to prolong the life of the unit. Centralized heating may be accomplished by circulating steam instead of boiled water. A steam system is more common in large ranges since it takes a large boiler and large amounts of water to supply adequate amounts of boiled water to heat a large range.

Certain boilers are classified as those that permit the grower to reduce the level of water to generate steam for pasteurization purposes. This process is called *trimming for steam* and is used when the greenhouse operation has no demand for hot water (e.g., in late spring or summer), since the heating system must be shut off during the process.

Solar Heaters A greenhouse by nature is a giant solar converter, only less efficient. Sunlight enters the facility through all of the transparent parts and is intercepted by objects in its path (e.g., the floor, soil, plants, and benches). These "collectors" store the energy for a short period and then release it into the atmosphere. Some modern greenhouses depend on solar heat collectors for heating. The initial investment for a solar heating system is high. As such, low-temperature solar systems are often preferred and used in conjunction with a conventional heating system for additional heating, especially in the winter season. A complete system consists of a collector, heat storage unit, heat exchanger, and control panel.

Biotherm Heating The floor of the greenhouse can be heated by laying down rows of flexible tubes (Figure 12–24). This strategy of heating a greenhouse, in which the soil is the primary target, favors enterprises in which pots and trays are placed directly on the floor (as often occurs in bedding plant production). The floor of the bench can also be heated by a similar method. This method of heating the greenhouse is called *biotherm heating.* Propagation benches benefit from heating from below.

Improving Heat Distribution

Notwithstanding the system of heating, it is crucial that heat generated be uniformly distributed throughout the greenhouse to prevent cold spots from occurring. Heat distribution is a more significant problem in large greenhouses than in small ones. When central heaters are used, heating pipes should be strategically located throughout the facility to effect uniform heating. Where cold spots occur, nearby plants grow slowly. The heating system should provide adequate heat not only for the aboveground plant parts but also for the root zone. In the case of unit heaters, attachments such as perforated polyethylene tubing located above the plants are used to aid in the distribution of warm air (Figure 12–25). The other important factor is that heaters should supply heat at a rate to offset what is lost by conduction, infiltration, and radiation.

FIGURE 12–24 Greenhouse floor heating. Hot water (90–120°F) is circulated through plastic pipes embedded in the (porous) concrete floor of this greenhouse. This heating system uniformly distributes heat ensuring uniform crop production. By providing heat where needed (i.e., close to the plants), the greenhouse aerial temperature can in some cases be lowered and, thus, reducing greenhouse heating costs. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

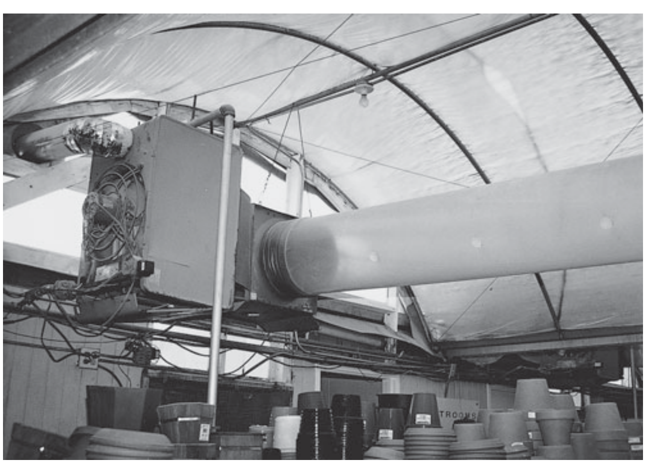

FIGURE 12–25 Perforated polyethylene tubing used for heat distribution in a greenhouse. *(Source: George Acquaah)*

Regulation of Heat

Thermostat
A device used to regulate temperature.

The regulation of heat is as important as its distribution. Heat cannot be continuously generated unless the conditions are such that it is lost as rapidly as it is produced. **Thermostats** are used to regulate heat in the greenhouse (Figure 12–26). In commercial greenhouses, aspirated thermostats provide effective control. This unit monitors the temperature of a continuous airflow caused by a tiny electrical fan. The greenhouse air is thus sampled continuously for more uniform control. Thermostats should be located at the height of growing plants so as to monitor the actual conditions of the plants. When the right temperature is attained, the heat should be turned off. To be on the safe side, emergency units should be provided as standby heaters in case the primary heat source fails during a crop production cycle. Large greenhouses are divided into sections that are monitored separately. These sections enable the greenhouse to be used for different enterprises simultaneously.

Conserving Heat

Heating a greenhouse is very expensive, and as such, every possible measure should be taken to conserve heat. The greenhouse should be inspected regularly to replace broken glasses, seal leaks, and clean boilers and heaters. As previously described, when polyethylene is used to glaze the frame of a greenhouse, a second sheet (i.e., double layer) creates a dead-air space between the layers for additional insulation.

Since most of the heat lost from a greenhouse is dispersed through the roof, the installation of an interior ceiling that can be drawn at night and opened during the day can conserve up to 30 percent of heat. For much greater heat conservation, *thermal screens* or sheets may be installed in the facility. These screens are installed on the ceilings and walls. Double thermal sheets are known to reduce fuel costs by more than 50 percent. Heat can be conserved by using fans installed in the ceiling to distribute the heat that would have been lost through the roof.

Ventilating and Cooling a Greenhouse

Greenhouse Ventilation Systems Ventilation is required to reduce excessive heat and humidity buildup in a greenhouse and aerate the environment with fresh air and fresh supplies of carbon dioxide for plant use. Since plants release oxygen and take in carbon dioxide, the carbon dioxide concentration in a closed system such as a greenhouse declines with time. The location of vents depends on the design and construction of the greenhouse. In an A-frame greenhouse, vents may be located in the ridge section of a side wall (Figure 12–27). Vents may be operated manually or be automated. Quonset greenhouses use forced-air ventilation (horizontal air flow) systems or side vents. There are two basic systems used in greenhouse air circulation—the **fan tube system** and the **high-volume, low-velocity fan system**. The former draws and distributes fresh air through perforated polyethylene tubes laid through the crop. The latter moves air through the entire length of

FIGURE 12–26 Aspirated box containing temperature and humidity sensors connected to the computerized environmental control system. Note that the box is located at a representative location and close to the crop canopy. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901).

FIGURE 12–27 Motorized ventilation inlet opening using the rack-and-pinion system. The opening area selected should ensure proper mixing of the incoming air with the greenhouse air. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901).

the greenhouse. Exhaust fans installed at one end of the greenhouse draw in fresh air through louvers installed at the opposite end (Figure 12–28). It should be pointed out that ventilation not only refreshes the greenhouse environment but also cools it.

Greenhouse Cooling Systems Although heat is required in winter and cool periods of the growing season, greenhouses need cooling in summer and warm periods. On the average, the ambient temperature in a greenhouse is about 11°C (20°F) higher than the outside temperature. Plants are damaged by both excessive heat and cold. Excessive heat can cause low crop yield through high flower abortion and drop. Greenhouses have vents that help circulate fresh air and provide cooling. However, in certain situations venting is not sufficient to reduce temperatures and cooling systems must be installed.

The most common way of cooling a greenhouse is by using an *evaporative cooling system* (Figure 12–29). This system involves drawing air through pads soaked with water, and hence is also called a *fan-and-pad cooling system.* The cooling pads are soaked with water dripping from above. These cross-fluted cellulose materials retain moisture quite well. Excelsior pads may also be used. The excess water is drained into a lower trough (sump) and recirculated by a pump. Warm air from outside is forced through the pads by the drawing action of fans at opposite ends of the greenhouse. In the process, some of the trickling water evaporates. Water evaporation removes heat from the air. The fan-and-pad cooling system uses the principle of evaporative cooling. To be effective, all incoming air should be drawn through the cooling pad. Cross-fluted cellulose pads, which look like corrugated cardboard, last longer than excelsior pads and are more popular.

Controlling Temperature

Controlling temperature should be distinguished from heating the greenhouse. Under conditions in which no heat is required, the temperature of the greenhouse should be maintained at an optimal level. The rule of thumb is to operate a greenhouse at a daytime temperature of 3 to 6°C (5 to 10°F) higher than the nighttime temperature on cloudy days and even higher (8°C or 15°F) on clear days. Since increasing the temperature accelerates growth, it must be done with care so as not to compromise the quality of the produce. Fast growth can cause spindly or thin stems and small flowers. Raising the temperature on a clear, bright day is necessary because light is not a limiting factor for photosynthesis under such conditions. Failure to raise the temperature may cause heat to become a limiting factor.

12.3.2 LIGHT

Light is required for photosynthesis and other growth activities. As previously explained, the light required by plants is described in terms of intensity, quality, and duration (Chapter 4).

FIGURE 12–28 Electric-driven ventilation fans used in stages to provide the required ventilation rate necessary to maintain set point temperatures. (*Source:* *Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901*)

FIGURE 12–29 Evaporative cooling pads used to cool the greenhouse when (mechanical) ventilation alone is not sufficient to maintain the desired set point temperature. The (wetted) pads are installed inside the ventilation inlet opening and outside air is drawn through them by ventilation fans installed in the opposite sidewall (not visible). Evaporative cooling is only successful when the relative humidity of the outside air is below saturation (100%). The drier the incoming air, the larger the temperature drop accomplished. Note that evaporative cooling increases the humidity of the greenhouse air. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901).

Intensity

On a clear summer day, plants in a greenhouse may receive as many as 12,000 foot-candles (or 129 kilolux) of light, an excessive amount for most crops, since by 3,000 foot-candles (32.3 kilolux), most plant leaves in the direct path of incoming light are light saturated and cannot increase their photosynthetic rate. Whole plants can utilize about 10,000 foot-candles (108 kilolux). Sunlight intensity is also seasonal, being less in winter and more in summer. Crops have different preferences and tolerances for light intensity. For example, foliage (nonflowering) plants are scorched and fade in light intensities above 2,000 to 3,000 foot-candles (21.5 to 32.3 kilolux). African violets lose green color at an even lower light intensity (1,500 foot-candles). Poinsettia plants are a darker shade of green when light is reduced. Also, plants such as geranium and chrysanthemum require shading in cultivation to prevent petal burn. Shading to reduce light by about 40 percent from midspring to midfall is helpful to prevent chloroplast suppression in most greenhouse plants. Greenhouse light intensity can be manipulated in several ways.

Shading In addition to fans and evaporative cooling systems, there are certain times during the year (early fall planting season and late spring harvesting period) when excessive heat buildup in detrimental to plant growth, fruit development, and ripening. Some modern greenhouses have retractable shade cloths that automatically deploy when radiation load on the greenhouse exceeds what the cooling systems can handle (Figure 12–30). In some designs the shade system is fixed (Figure 12–31). Shading the greenhouse to reduce excessive light is accomplished in several ways. Glass greenhouses may be sprayed with paint (whitewash) in summer to reflect light and reduce its intensity. Commercial shading paints may be purchased. A screen made from fabric may be more convenient to use if only a section of the greenhouse requires shading. Durable fabrics include polyester and polypropylene; they are available in different densities of

FIGURE 12–30 Movable internal shade curtain. Note that curtains can be mounted in a variety of greenhouse designs, including designs with a fair amount of overhead installations (heating and irrigation pipes, supplemental lighting, etc.). The curtain fabric is selected based on the two functions it is to perform: reflect sunlight (during the summer and particularly the middle of the day) and heat (at night and during the winter months). (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

FIGURE 12–31 Fixed external shade curtain. Compared to internal shade curtains, these systems reduce the amount of heat entering the greenhouse (requiring removal by the ventilation and/or cooling system). External shade curtains are particularly practical for crops requiring low light levels. (*Source: Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)*

weave for providing degrees of shading from 20 to 90 percent, 50 percent being the most common. Some modern greenhouses have retractable shades that are used as needed. Saran may be used to cover plants in sections of a greenhouse or bench. Also, aluminized strips may be used to create an interior ceiling that can be drawn on sunny days.

Undesirable shading may be inherent in the design of the greenhouse. Materials for construction and design of the frame, cooling systems, and plumbing and light fixtures that are located overhead intercept incoming light. The narrower the frame material, the better. Overall, these obstructions may reduce greenhouse light intensity by 30 percent or more. Further, seasonal and daily light intensity reductions may be caused by the orientation of the greenhouse and the characteristics of the location.

Plant Density Plants may also be spaced to utilize incoming light. In summer, closer spacing should be used, whereas wider spacing is recommended in winter. Spacing–light intensity interaction can be manipulated to control the size of plants, since the same amount of dry matter will be produced under an available light intensity. Therefore, to obtain larger plants, space widely; to obtain smaller plants, space closely.

Washing To increase light intensity, the glass covering of the greenhouse should be cleaned (Figure 12–32). Dust particles on the glass plates reduce intensity by up to about 20 percent. Washing by running water through a hose may not be sufficient. A cleaning solution should be used (e.g., 11 pounds [5.0 kilograms] of oxalic acid dissolved in 33 gallons [150.2 liters] of water may be sprayed onto a damp, dirty greenhouse and hosed down with water after three days). Other greenhouse types also need periodic cleaning.

Supplemental Lighting

In winter or darker periods (middle of fall to early spring season), supplemental lighting may be required by certain plants for good growth and quality. When needed, it may be supplied by using a variety of sources, categorized as follows.

FIGURE 12–32 A machine used to clean the roof glass of a Venlo-type greenhouse. Over time, dust and dirt accumulation can significantly reduce light transmission into the greenhouse. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

Incandescent Lamp Incandescent lamps have tungsten filaments. They are not desirable for greenhouse use because, in addition to light, they generate excessive heat. Incandescent lamps characteristically emit a high proportion of red and far red light, which produces abnormal growth in some plants (e.g., soft growth or induced tallness). They are very inefficient, converting less than 10 percent of the electrical energy consumed into light.

Fluorescent Lamps Fluorescent lamps are energy efficient (20 percent electrical energy converted to light) and produce little heat. However, because they are low-power sources, many of them are often required to produce the desired intensity. Consequently, a large number of fixtures must be installed. These installations end up blocking incoming natural light. They are commonly used in growth rooms where seeds are germinated or in small greenhouses. The cool white model, which provides light of predominantly blue wavelength, is commonly used. However, fluorescent tubes with capacities to emit a superior quality of light for photosynthesis are available. One class, called *plant growth A,* produces light in the red region of the light spectrum; another class of tubes, *plant growth B,* has capabilities for emitting radiation beyond the 700-nanometer wavelength.

High-Intensity-Discharge Lamps As their name indicates, high-intensity-discharge lamps can generate intense light (Figure 12–33). There are several types and designs available: high-pressure mercury discharge, high-pressure metal halide, and high-pressure sodium light. In certain types, power ratings may be as high as 2,000 watts. The high-pressure sodium lamps are less expensive than the others to install and operate and can generate up to 1,000 watts of power for 24,000 hours. The light quality emitted is in the 700- to 800-nanometer spectral range. Low-pressure versions of the high-pressure sodium lamps are available. Considered the most efficient lamps for supplemental greenhouse lighting (27 percent electrical energy converted to light), they are available in power ratings of up to the popular 180-watt size. However, these lamps are deficient in quality of light produced and do not emit enough light in the 700- to 850-nanometer range. Therefore, when used alone, plants often develop abnormally (e.g., pale foliage in lettuce and petunia). When used in combination with daylight or

FIGURE 12–33 A high pressure sodium (HPS) lamp consisting of a bulb, a reflector, and housing containing a current-regulating ballast and related electrical components. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901).

another appropriate source, plant growth problems are eliminated. Supplemental lights in growth rooms can double up as heat sources, except in very cold seasons.

Height of Light

The various types of lamps emit light at different intensities, ranging from about 2,000 to 11,000 lux (185 to 1,000 foot-candles), or even higher in some cases, as in growth rooms. The effect of each source depends not only on the power rating of the unit but also on the arrangement and height above the plants. For example, if a 4-foot-wide (1.2-meter-wide) bed of plants is to be illuminated using one row of 60-watt bulbs spaced 4 feet (1.2 meters) apart, the arrangement should be hung no more than 5 feet (1.5 meters) above the soil. Fluorescent tubes are used widely in growth rooms because they provide uniform light intensity over a wide area. Using cool white lamps (at 125 watts), seven tubes mounted 1.5 to 2 feet (0.45 to 0.62 meters) above the soil provide low-intensity light for a 3.5-foot-wide (1.1-meter-wide) bench.

Incandescent light installed at about 2 to 3 feet above the plants to generate 10 foot-candles of light intensity is referred to as *standard mum lighting*. At this intensity, flower formation is prevented so that plant growth is stimulated during the short nights of summer. Poinsettia plants can be kept vegetatively by using this treatment. It is important that light intensity be monitored periodically to ensure that the crop receives at least 10 foot-candles of light. Sometimes reflectors (e.g., aluminum foil) may be installed above the lightbulbs to direct more light to plants. High-density lamps are usually encased in reflectors. They have a higher output and are hence hung higher above the plants.

Duration

Duration of light *(photoperiod)* is a precise time-tracking mechanism (Chapter 4). Even changes between duration of light and darkness that deviate minutely could spell disaster in certain situations. Plants are traditionally categorized as *long day, short day,* or *day because neutral* As already indicated, this is a misnomer, the tracking mechanism actually relates to the duration of darkness rather than daylight.

The importance of controlling photoperiod lies in the consequences of not doing so. In poinsettia, the red (or other color) pigmentation in the bracts depends on photoperiod, similar to flowering in chrysanthemum. Short nights are required for asters and lettuce to bolt (form stems and flower). Under short-night conditions, dahlias are prevented from producing tubers and thus produce flowers instead.

On the other hand, plants such as kalanchoe, azalea, and chrysanthemum flower when nights are long. When nights are long, dahlias form tubers instead of flowers; bryophyllum leaves produce plantlets along the margin when nights are long. For some plants, the duration of night length is not inhibitory to flowering, but the process occurs much more quickly under ideal conditions. These plants are called **facultative short-night** (e.g., carnations) or **facultative long-night** (e.g., Rieger begonias) plants. As indicated previously, photoperiod is influenced by other factors such as temperature, species, and maturity. Plants such as roses are day neutral.

Facultative Long- and Short-night Plants
Plants that do not require a specific duration of dark period for a response to occur, but will respond faster if the dark period is extended or shortened, respectively.

Cyclic Lighting
A method of light application where the total duration of light is reduced by approximately 80 percent by replacing continuous lighting with intermittent lighting of about 6 cycles of 5 minutes of light and 25 minutes of darkness.

Extending Day Length To control photoperiod, incandescent lamps are best for extending the day length in short-night treatments because they emit light in the red wavelength of the light spectrum. The Pr *phytochrome* (red phytochrome) responds to this light. To reduce the cost of short-night treatment, intermittent lighting (called **cyclic lighting,** or *flash lighting* is sometimes used instead of continuous lighting over the prescribed duration of light interruption. The duration of short-night treatment depends on whether the crop is planted in winter or summer. Nights are naturally short in summer, and therefore no interruption may be necessary then. Short-night treatment involving turning lights on for two to eight weeks is necessary during the winter. The treatment may be administered by turning lights on during the late afternoon to extend the day or interrupting the dark period during the middle of the night (for a shorter duration). The number of hours of supplemental light also increases toward December. The latitude plays a significant role in the duration of light interruption, since northern latitudes experience shorter summer nights and longer winter nights.

Decreasing Day Length Plants that require decreasing day length treatment flower only when they are exposed to extended periods of darkness. In commercial greenhouses, black cloth is used to block out light at the desired time and removed after the required period (usually from 7 P.M. to 7 A.M.). Light blocking may be done mechanically (very laborious) or automatically. Care must be taken to provide complete darkness since leaks that let in light can cause aberrant developments such as hollow flower buds (crown buds).

12.3.3 WATER

Water is critical to the quality of plant products produced under greenhouse conditions. Plants are adversely affected by both excessive and inadequate moisture supplies. Overwatering can injure plant roots by creating anaerobic conditions in the root zone. Because air pores are occupied by water, plants may wilt and die or become stunted in growth. Too-frequent watering may produce excessive tissue succulence, making plants weak. Moisture stress from infrequent watering may cause plants to wilt or grow at a slow rate. Plant leaves may become small and the general plant stature stunted, with short internodes.

A successful watering regime depends on a well-constituted growing medium. The medium must drain freely while holding adequate moisture for plant growth. The purpose of watering is not to wet the soil surface but to move water into the root zone. The growing medium should be watered thoroughly at each application, requiring that excess water be drained out of the pot. This practice also prevents the buildup of excessive amounts of salts from fertilizer application. Excessive watering is not due to one application but rather is the result of watering repeatedly when it is not needed. When watering frequency is too high, the soil is prone to waterlogging and poor aeration. Roots need to breathe and thus must not be constantly under water. A good watering regime is one that applies water in a timely fashion, just before plants go into moisture stress. This stage must be ascertained through keen observation and experience. It is recommended that about 10 percent of water applied to a pot drain out of the bottom of the container. This amount ensures that the soil is thoroughly wet, and aids in flushing out excessive salts that may have accumulated as a result of fertilizer applied over a period. A 6-inch (12.2-centimeter) azalea pot should receive 10 to 20 ounces (283.5 to 567 grams) of water, an amount that must be adjusted according to the kind of soil (soilless or real soil mix).

Source of Water

The quality of local water depends on its source because of groundwater pollution problems and water treatment programs. Even where domestic water is used for irrigation, it should be noted that cities treat their water differently. Some add fluoride (called *fluoridation*) to reduce tooth decay in humans. Unfortunately, many plants, including the spider plant *(Chlorophytum),* corn plant *(Drocaena fragrans),* and spineless yucca *(Yucca elephantipes),* are sensitive to and injured by fluoride. Most of these plants belong to the families Liliaceae and Marantaceae. Chlorine is less of a problem but nonetheless injurious to some plants, such as roses, when the concentration reaches about 0.4 parts per million (ppm). When the source of water is a well, the level of soluble salts (sodium and boron) is often high. Many arid coastal regions have high boron toxicity; liming of soil reduces the potential for this problem. Bicarbonate is another water pollutant that affects plant growth.

Water Application Methods

Hand Watering The age-old method of hand watering by using a watering container or water hose is appropriate for small-scale watering. When a large area is involved, commercial companies often use automated systems. Even then, hand watering may be best and is thus used on certain occasions. The devices used are equipped with nozzles designed for a variety of situations. Some provide fine, misty sprays and others coarser sprays. Watering seedlings and newly sown seeds requires a fine spray. Applying water uniformly is difficult when hand watering. One of the advantages of hand watering is the instant judgment of the operator as to whether a plant needs water. Also, a keen operator can observe any problems (e.g., diseases and insect pests) during hand watering.

Automatic Watering Systems Automatic watering systems differ in cost, efficiency, and flexibility. Some are semiautomatic and must be switched on and off. In a truly automatic system, the operation is controlled by a programmable timer, which allows watering to occur for a specified period.

Tube Watering Growers use sophisticated methods of water application for premium-quality produce. The tube watering system is the most widely used system of watering for potted plants. When flowers are grown for the fresh flower market, they must be clean. Water is administered only to the soil in the bed without splashing on the plants, which reduces the chance for disease spread. By using microtubes, individual pots can be automatically watered to provide water in the right amounts and at the right frequency for high quality. Two commonly used tube watering systems are the Chapin and Stuppy® systems. The difference between the two lies in the weights at the end of each tube. The Chapin system uses a lead weight, and the Stuppy uses plastic (Figure 12–34). Tube watering is also amenable to the application of water-soluble chemicals (e.g., growth hormones and fertilizers). The system is expensive to install and not flexible. Pots on the bench have to be uniform in size, and the tubes must be inspected periodically to ensure that no blockage exists.

Capillary Mat The capillary mat is a subirrigation system in which potted plants are placed on a water-absorbing fiber mat covered with a perforated plastic sheet (Figure 12–35). Water is absorbed by capillary action through the drainage holes in the bottoms of the pots. The mat is kept moist by tubes installed on the bench. Potted plants such as African violets are watered by this method. A capillary mat is flexible and easy to install. Different pot sizes can be accommodated simultaneously. Further, it is easy to rearrange plants as required by growth. For the system to work properly, the mat must be placed on a level surface. One problem with using a capillary mat is the growth of algae.

Overhead Sprinklers When used on ground beds, nozzles are mounted on risers whose height depends on the mature height of the crop (Figure 12–36). For plants on benches, the sprinkler nozzles may be suspended above the plants. Overhead sprinklers wet the foliage and predispose it to diseases (Figure 12–37). Watering should be done

FIGURE 12–34 Microirrigation system. Also called the tube, or "spaghetti," watering system.

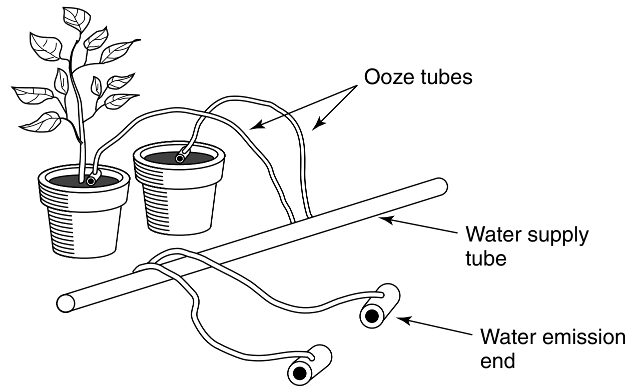

FIGURE 12–35 A capillary mat watering system.

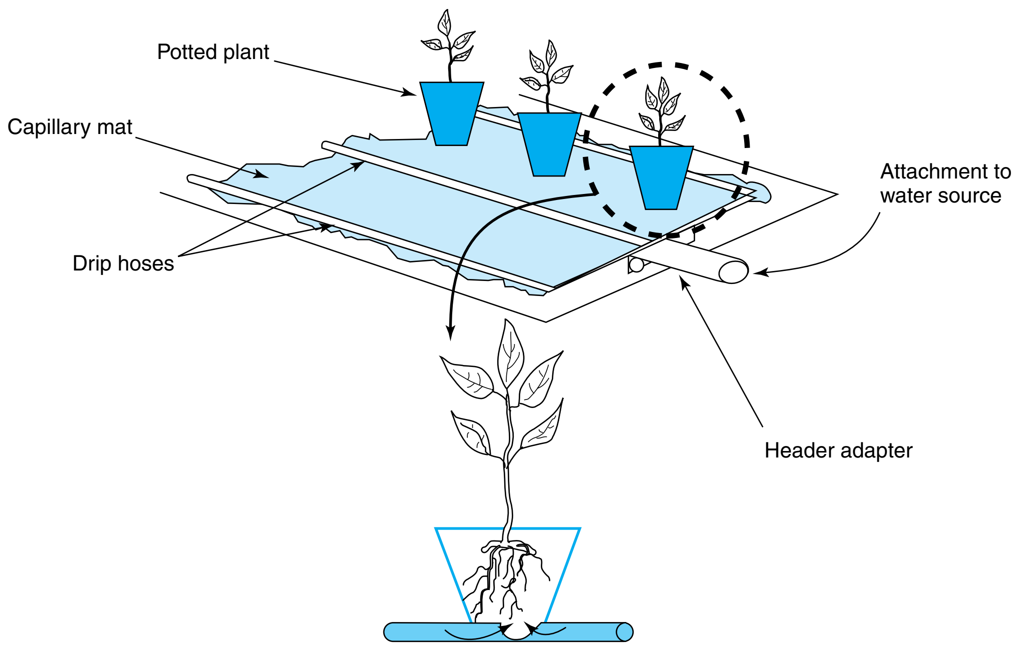

FIGURE 12–36 An overhead irrigation system for watering plants on greenhouse benches. *(Source: George Acquaah)*

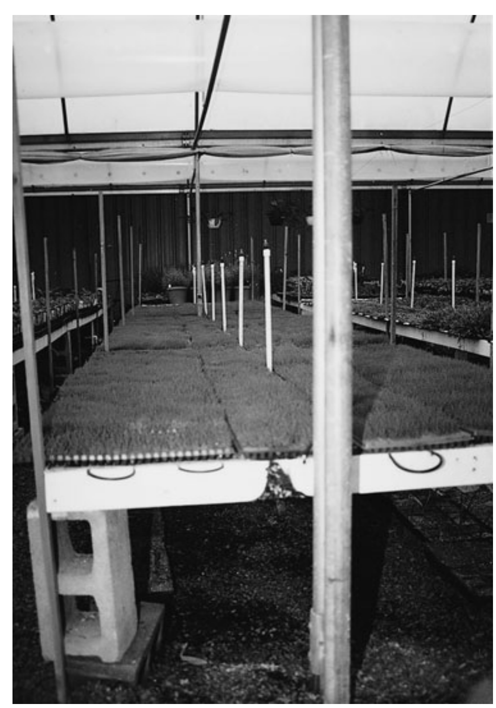

FIGURE 12–37 Overhead sprinkler irrigation system. Such a system is relatively simple to install and operate, but results in significant leaf wetting during irrigation. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901).

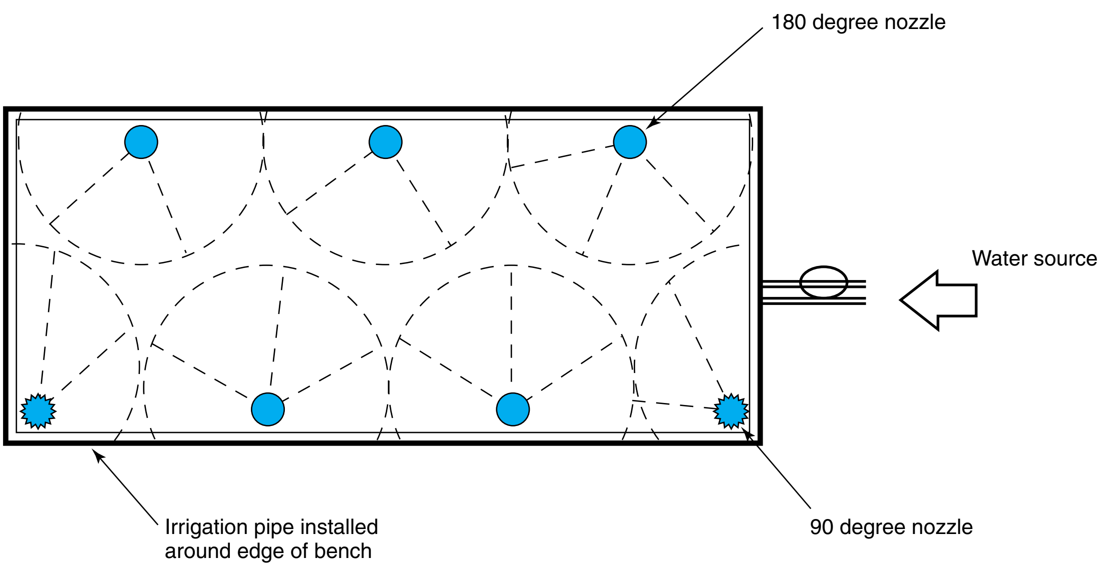

FIGURE 12–38 Perimeter watering of a greenhouse bench.

in the morning to give plant foliage a chance to dry during the day. This system is used widely for watering bedding plants.

Perimeter Watering The cut flower industry cannot afford to have blemishes on foliage and flowers. The perimeter watering system is a method of greenhouse irrigation in which water is provided without wetting the foliage of the plants (Figure 12–38). Sprinkler nozzles are installed along the perimeter of the bench. These nozzles deliver a flat spray, and thus the foliage and the part of the plant stem to be included in cut flowers are not wet. The water must be sprinkled at a high enough pressure to reach plants in the center of the bench.

Israeli Drip System (For Hanging Baskets) The Israeli drip system of watering hanging baskets involves hanging plants on a support pipe at intervals that coincide with drip points on a plastic pipe located under the support pipe (Figure 12–39). The disadvantage of this system is that water drips on foliage, predisposing it to disease. To minimize this problem, plants should be watered early in the morning so that they have a long time to dry before nightfall. A modern and efficient way of watering hanging baskets is the use of carousels (Figure 12–40).

Misting Misting systems provide very fine sprays of water. They are used on plant propagation benches or beds. Mists are produced from sprinklers fitted with nozzles for very fine sprays.

Polyethylene Tubing Perforated plastic pipes may be used to water cut flowers. Pipes are laid between rows of plants in the bed.

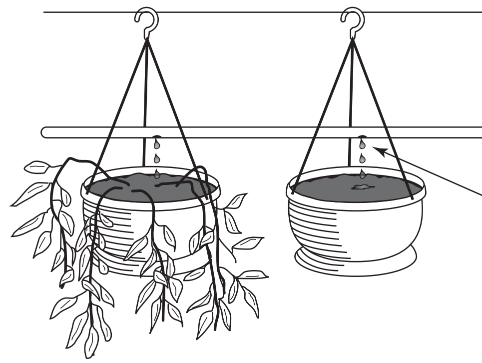

FIGURE 12–39 An Israeli drip irrigation system for hanging baskets.

FIGURE 12–40 Irrigation carousel for hanging baskets. A single irrigation point can service an entire string of hanging baskets as they are automatically moved one-by-one past the irrigation point. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901).

12.3.4 GREENHOUSE FERTILIZATION

Plants grow in a restrictive environment in a greenhouse. The volume of the growing medium in a pot is only a fraction of that available to plants in the field. Further, the growing medium may be soilless and hence require nutritional supplementation, especially micronutrients. As compared to field fertilization of crops, greenhouse crops sometimes receive a hundredfold of the fertilizer applied in the field. Organic fertilizers are not commonly used in greenhouse plant production because they do not lend themselves to automation (e.g., application through irrigation water). They tend to have odors that make their use under enclosed conditions unpleasant. Further, it is difficult to apply exact concentrations of nutrient elements when using organic fertilizers. Fertilizers are discussed in detail in Chapter 4.

Inorganic Fertilizers

Inorganic fertilizers are convenient to apply and amenable to a variety of methods of application, including through irrigation water. Inorganic fertilizers can be applied in exact amounts as needed. Dry and liquid fertilizers are used in the greenhouse, the more common being liquid fertilizers, which are applied through the irrigation water. Another form of fertilizer used in greenhouses is slow-release fertilizer it is highly desirable because nutrients are released over a period of time and thus better utilized.

Methods of Application of Liquid Fertilizer

Liquid fertilizers may be applied to plants in the greenhouse in several ways.

Constant Feed Constant-feed application entails administering low concentrations of fertilizer each time the plant is irrigated. It mimics the slow-release fertilizer action and is the most popular method of greenhouse fertilization. This method is desirable because plants receive a fairly constant supply of nutrients in the soil for sustained growth and development.

Intermittent Feed Greenhouse plants may be fertilized according to a periodic schedule such as weekly, biweekly, or monthly. The disadvantage of this method is that the high level of nutrition available at the time of application gradually decreases over time until the next application. Plant growth is thus not sustained at one level but fluctuates.

Automation

To eliminate the tedium in preparing fertilizer solutions each time an application is to be made, growers usually prepare concentrated stock solutions that are stored in stock tanks. By using devices called fertilizer injectors (also commonly called **proportioners,** since most of them are of this type), the desired rate of fertilizer is applied through the irrigation water, a process called **fertigation** (Figure 12–41).

Proportioner
A device used in a fertigation system to control the rate of fertilizer applied through the system.

Fertigation
The application of fertilizers in soluble form through an irrigation system.

Measuring Fertilizer Concentrations

Nutrients may be applied as solids or liquids. When in solid form, they are either mixed in with the medium or applied in the form of slow-release fertilizer. Fertilizer is often applied through the irrigation water; these fertilizers must thus be water soluble. They are formulated as high concentrations of the elements they contain and must be diluted before use. The most common greenhouse fertilizer grade is 20-20-20.

Liquid fertilizer concentrations used in greenhouses are measured in parts per million. To prepare a stock solution to a desired concentration, the grower needs to know the proportioner ratio, stock tank volume, rate of application intended, and fertilizer analysis of the fertilizer source.

The formula for calculating stock concentrations is as follows:

1. ounces/100 gallons of water = ppm desired/% element $\times$ correction factor $\times$ 0.75

where correction factors are % P = % $P_2O_5 \times 0.44$

% K = % $K_2O \times 0.83$

(No correction is needed for nitrogen.)

Example: A nursery grower would like to fertilize his plants at the rate of 275 ppm of nitrogen. He purchases a complete fertilizer of analysis 20:10:20 and intends to use a 1:200 proportioner for the application. His stock tank can hold 50 gallons (227 liters) of liquid. How many pounds of the fertilizer should be dissolved in his stock tank?

Solution:

ounces/100 gallons = 275/20 $\times$ 1 $\times$ 0.75

= 275/15

= 18.33 pounds

(a)


(b)


FIGURE 12–41 (a) Control and display units for a fertilizer and acid injection system, (b) Components of a fertilizer and acid injection system. Fresh make-up water and/or water returning from an irrigation cycle is checked and adjusted for the proper nutrient concentration (EC: electrical conductivity) and pH. (*Source:* Dr. AJ Both, Bioresource Engineering, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, NJ 08901)

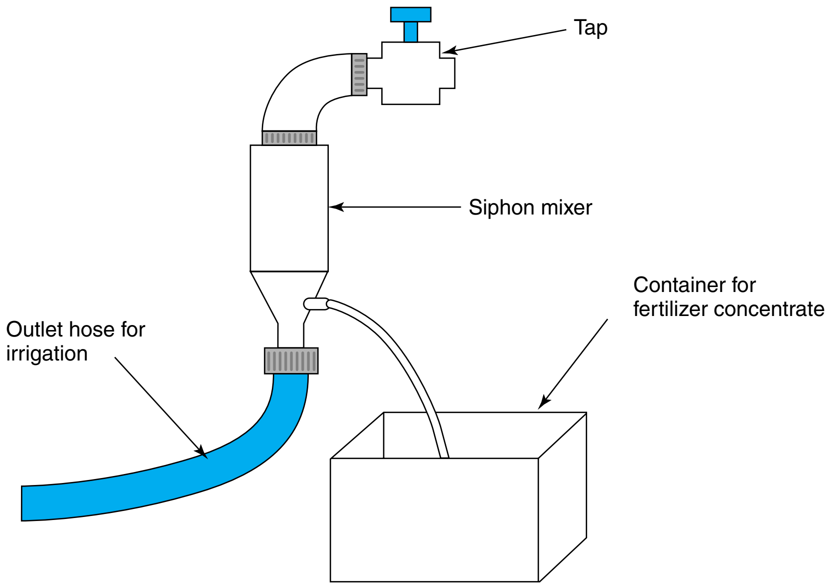

FIGURE 12–42 A Venturi-type proportioner.

2. Preparing the stock solution.

pounds to add to stock tank:

= ounces/100 gallons × second number of injector × stock tank volume (gallons)/100 × 16

= 18.3 × 200 × 50/100 × 16

= 183,000/1,600

= 114.4

Proportioners are calibrated in terms of the ratio of dilution of concentrated fertilizer with irrigation water. Some have fixed ratios (e.g., 1:100 or 1:200), and others are variable. They differ in mechanisms of operation, proportioning ratio, and cost. A relatively inexpensive type is the Hozon proportioner, which operates on the Venturi principle (Figure 12–42). Water enters the unit at very high velocity, generating a suction in a feeder line that is dipped into the soluble fertilizer concentrate. The suction draws the fertilizer into the watering hose, where it mixes with tap water according to a predetermined concentration. Proportioners may lose their accuracy over time and require periodic callibration.

Problem of Accumulation of Soluble Salts Pot media are prone to accumulation of soluble salts, which may result from factors such as poor drainage, excessive fertilization, or insufficient irrigation (resulting in inefficient leaching). Such accumulation may result in toxicity or deficiency of certain minerals. Monitoring the soluble-salt content of growing media, which can be done with an instrument called a *solubridge,* is important.

Fertilizers differ in solubility and *salt index* (a measure of the effect of a fertilizer on the soil solution. Potassium chloride has a salt index of 116, and urea, ammonia, and regular superphosphate have salt indices of 75, 47, and 8, respectively. Fertilizers of low salt indices are preferred to reduce salt accumulation. A greenhouse water supply may contribute to the amount of soluble salts in the soil or growing medium.

12.3.5 CARBON DIOXIDE FERTILIZATION

Plants utilize carbon dioxide and water in the presence of light to manufacture food by the process of photosynthesis. Carbon dioxide occurs in the atmosphere in a low concentration of about 350 ppm. As long as adequate ventilation and freely circulating air are present, greenhouses receive sufficient amounts of carbon dioxide for photosynthesis.

However, in winter, greenhouse vents are closed for more efficient heating. Because plants use carbon dioxide (animals and other combustion processes produce the gas as by-products of respiration or burning of fuel), the supply of this gas in an airtight greenhouse is limited, which in turn decreases the rate of photosynthesis. Under such conditions, the greenhouse environment may be enriched with supplemental carbon dioxide by burning natural gas in an open flame or using compressed gas or dry ice (solid, frozen carbon dioxide that is used in other laboratory procedures as well). Propane gas burners may also be used to generate carbon dioxide. The goal of **carbon dioxide fertilization** is to raise the concentration of the gas to about 1,000 to 1,500 ppm. This high level of carbon dioxide must be provided along with bright light (e.g., bright daylight) for it to be beneficial to plants. In addition to light, heat is a limiting factor to the effectiveness of carbon dioxide fertilization. Lettuce plant weight increased by more than 30 percent at 1,600 ppm of carbon dioxide. Certain crops have been known to flower earlier under carbon dioxide fertilization. Some of the equipment used to provide additional carbon dioxide may release undesirable toxic gases such as carbon monoxide and ethylene during combustion of the fuel; such gases are toxic to both plants and animals.

Carbon Dioxide Fertilization
Deliberately increasing the carbon dioxide concentration in the air of the greenhouse to increase the rate of photosynthesis.

12.4 Greenhouse Pests

The use of pesticides (especially those that are volatile) in enclosed places is a potential health hazard to humans present in those areas. Every effort should be made to minimize the introduction of pathogens and weeds into a greenhouse. Weeds may grow in greenhouses with gravel or porous concrete floors. Apart from being unsightly, weeds may harbor insects and other pests. Weed seeds may be blown into the house or carried in potting media and impure crop seed. If required, only chemicals approved for greenhouse use (e.g., Roundup) may be used. Common greenhouse diseases include root rot, damping-off, botrytis blight, powdery mildew, and root-knot nematodes. Disease incidence can be reduced through strict observance of sanitation. Pots and all containers should be sterilized before reuse. After each crop cycle, the benches should be scrubbed and sterilized. Unsterilized media should not be allowed into the greenhouse. It is recommended that a greenhouse operator maintain a regular schedule of preventive programs. Since many greenhouse plants are grown largely for aesthetic uses, any blemish reduces the price that can be obtained for a product. A wide range of pests are found in the greenhouse, including aphids, fungus gnats, thrips, mealybugs, leaf miners, mites, and whiteflies.

Sometimes the grower has no choice but to use pesticides. On such occasions, the safest products and those recommended for greenhouse use must be selected. After a spray or fog application of a pesticide, the greenhouse must be aerated before people are allowed to work in the facility. Greenhouses may attract rodents (especially mice and rats), depending on the activities taking place in the facility and how it is kept. Baits and traps may be placed at strategic places to catch these rodents.

An effective approach to controlling pests in the greenhouse is the adoption of greenhouse-specific integrated pest management (IPM) programs. Such programs entail a combination of strategies, namely, sanitation, physical control, biological control, and use of pesticides. It should be pointed out that IPM will work properly in a greenhouse if the facility is used for a specific plant or crop or can be partitioned into sections for specific activities. IPM programs may include regular fumigation, washing and disinfecting floors, spraying, and other sanitary precautions. Plant debris should be removed and disposed of without delay, since debris may harbor pests.

One way of keeping plants healthy is to provide adequate growth factors (nutrients, light, temperature, water, and air). Healthy plants are more equipped to resist attacks from pests. To prevent entry of flying insects, ventilators may be covered with fine mesh screens. Other physical control measures include the use of yellow sticky traps. These traps have a dual purpose—monitoring the level of insect infestation and reducing their population (since once captured they die). For ground beds, plastic mulches may be used to suppress weeds.

Improved cultivars of horticultural plants with resistance to various diseases and pests have been developed by plant breeders. Some cultivars are better suited to greenhouse production than others. Tools should be cleaned and properly stored after use. Phytosanitary observance is also critical. All plant remains must be discarded.

Summary

Plants may be grown in or out of season by growing them under controlled-environment conditions in greenhouses. Under indoor conditions, some or all natural growth requirements may either be supplemented or controlled in order to provide the appropriate amounts at the right times. Greenhouses differ in design, efficiency, and cost of construction and operation. Film-plastic models are cheaper to construct but less durable. More expensive and durable materials are glass and fiberglass-reinforced plastics.

An advantage of growing plants in an enclosed environment is that the optimal growth factors can be provided with minimal fluctuations. Heat during the cold season is provided by using heaters that burn fuel (e.g., unit heaters) or those that do not burn fuel (e.g., radiant heaters). Greenhouse heat may be lost through conduction, infiltration, or radiation, conduction being the major avenue. In summer, greenhouses are cooled by using cooling systems such as the evaporative cooling system. Light intensity, which increases during summer, is controlled by shading with fabric or whitewashing the glass outer covering of the greenhouse. During the winter months when light intensity decreases, the paint is washed away. Sunlight is supplemented with artificial lights from a variety of sources, including incandescent lights, fluorescent lamps, and high-intensity-discharge lamps.

Water used in greenhouses often comes from the domestic supply system. Care must be taken not to overwater greenhouse plants, which are generally planted in pots. The soil must be freely draining. The nutrient supply is important since the growing medium may be a soilless mixture, which will be low in nutrients or have none at all. Since the growing plant has a limited soil volume from which to forage for essential nutrients, the soil quickly becomes depleted of minerals and needs replenishing on a regular basis. Slow-release fertilizers are a good choice for greenhouse fertilizer applications.

References and Suggested Reading

McMahon, R. W. 1992. *An introduction to greenhouse production*. Columbus Ohio Agriculture Education Curricular Material Services.

Nelson, P. V. 1985. *Greenhouse operation and management*, 3d ed. Retson, Va.: Retson Publishing.

Ortho Book Staff. 1979. *How to build and use greenhouses*. San Francisco: Ortho Books.

Sunset Book Editors. 1976. *Greenhouse gardening*. Menlo Park, Calif.: Sunset-Lane.

Walls, I. G. 1991. *The complete book on the greenhouse*. London: Wardlock.

Greenhouse construction
http://www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management/jb_buildi_ng_gh.htm.

Practical Experience

Conduct a field trip to commercial or research greenhouses. On the trip, find out about the greenhouse design type, materials used, purpose of the unit, how it is cooled and heated, various types of automation systems, layout of the benches, kinds of plants grown, and so forth.

OUTCOMES ASSESSMENT

1. Explain the underlying principles of a greenhouse design.
2. Discuss the advantages of gutter-connected greenhouses.
3. Compare contrast glass, polyethylene, and fiberglass as glazing material for greenhouse.
4. Discuss the management of heat in greenhouse production.
5. Describe how greenhouse producers manage light for optimal crop growth.
6. In what ways does fertilization of greenhouse plants differ from fertilization of field crops?
7. Describe how greenhouse design can optimize the use of greenhouse space.
8. The following exercises are designed to help the student better understand greenhouse energy issues. They were developed by Dr. AJ Both and Dr. David Mears of the Bioresource Engineering Department of Plant Biology and Pathology Rutgers University, New Brunswick, NJ:

Heat loss through any portion of a greenhouse structure can be calculated by multiplying a heat transfer coefficient times the area of the portion of the structure being considered times the temperature difference between inside and outside. The heat transfer coefficient depends on the material covering that portion of the structure and to some extent the external weather conditions. Approximate heat transfer coefficient for various glazing systems can be found in the reference and generally include a factor to account for some air infiltration for a reasonably well-sealed greenhouse. The total heat loss for any greenhouse can be calculated by adding up the heat loss the each portion. In the English systems of units the heat transfer coefficient is in British thermal units per hour per square foot per degree Fahrenheit, Btu/(hr$*$ft^{2*}°F) so when coefficient is multiplied by the area and temperature difference it is the Btu/hr lost through that portion of the structure.

1. Consider a 96-foot long hoop house made by bending 12-foot water pipes into a semicircle with the roof and ends covered with double-laver polyethylene. If the heat transfer coefficient for plain double-layer polyethylene is Btu/(hr$*$ft^{2*}°F) and it is 0°F outside when the crop requires 60°F inside what is the hourly heat requirement under these conditions?
2. Consider a larger, gutter-connected greenhouse with 7 bays, each 30 feet wide by 210 feet long with 12 feet height to the gutter and 19.5 feet to the ridge. The roof section, side walls, and gable end walls are all to be glazed with a single layer of glass with a heat transfer coefficient of Btu/(hr$*$ft^{2*}°F). For the same inside and outside temperature conditions as in problem 1, what is the total hourly heat requirement for this structure?
3. To change this greenhouse to double-layer polyethylene on roof and all walls, the straight rafters are changed to curved bows each one 34.5 feet long. Assuming the average end wall heights is 14 feet and using the same heat transfer coefficient and the same temperature conditions as in problem 1, what is the total hourly heat requirement for this structure?
4. For each of the first three problems, divide the total heat requirement by the floor area of the greenhouse to compare the heat requirement per unit floor area. Discuss the differences of the results in problems 1 and 2 and the differences of the results of problem 2 and 3.
5. For an advanced exercise look up the heat transfer coefficient for double-layer polyethylene with an infrared heat-absorbing additive in the references or from an Internet source, and discuss the energy saving possible. Do the same for the gutter-connected greenhouse with the addition of a movable shade/heat retention curtain system.