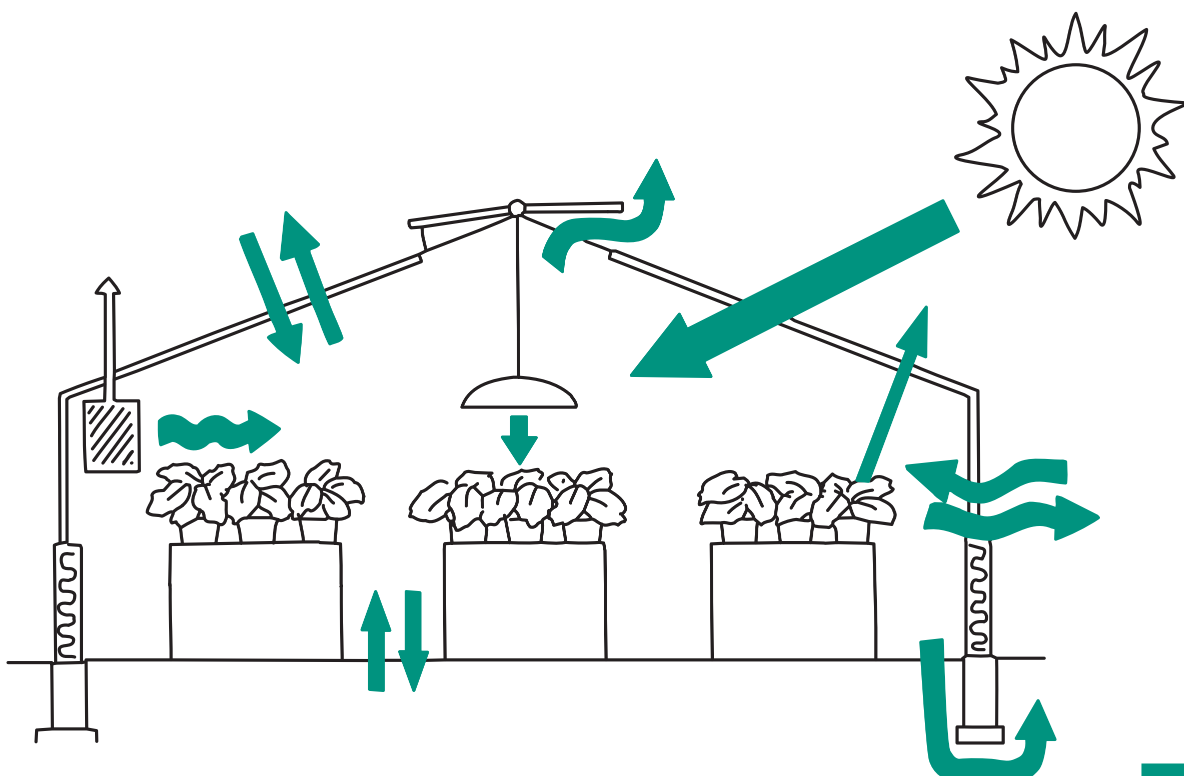
NRAES–3
2001 Revision

Energy Conservation for Commercial Greenhouses



Natural Resource, Agriculture, and Engineering Service (NRAES)
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Energy Conservation for Commercial Greenhouses was first published by NRAES in 1978. It underwent minor revisions in 1979, 1985, and 1989. This 2001 revision contains more extensive changes — information has been updated to reflect current technology and trends; chapters on utilities, trucking costs, and management have been added; and new tables and illustrations have been added. Authors of the previous version of *Energy Conservation for Commercial Greenhouses* are listed on the title page at right.

This revision was peer-reviewed by the persons listed below. It was judged to be technically accurate and useful for cooperative extension programs and for the intended audience. The author is grateful for the comments provided by reviewers, as they helped to add clarity and depth to the information in this book.

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Cooperative Extension

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2001 Revision

Energy Conservation for Commercial Greenhouses

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Introduction

High energy costs and greater difficulty in obtaining new sources make conservation an important part of a greenhouse operation. New greenhouse design principles, better glazings and insulating materials, improved heating and ventilating systems, and new management methods make today's greenhouses much more efficient than those only a few years old.

In traditional greenhouse operations, space heating requires the greatest expenditure of energy. In a northern U.S. greenhouse, heating consumes 70–80% of the total energy needed (figure 1a). Electricity for fans, pumps, and other equipment consumes 10–15% of the total. Depending on whether the business is wholesale or retail, gasoline and diesel fuel will consume 5–10%.

For most greenhouse operations, the rising cost of energy has made it the second largest cost item in producing plants behind labor. While great savings can be realized through planning and effectively using energy-saving technology and management systems, the primary objective is to produce crops profitably. Any system that unduly increases labor, limits crop production, or decreases crop quality needs to be carefully studied.

This book reviews the merits and limitations of current energy-conservation strategies. It provides many viable options and helps managers make decisions that best fit their operations. Choosing a particular system will depend on how it fits in with the production system, management practices, and profitability margin.

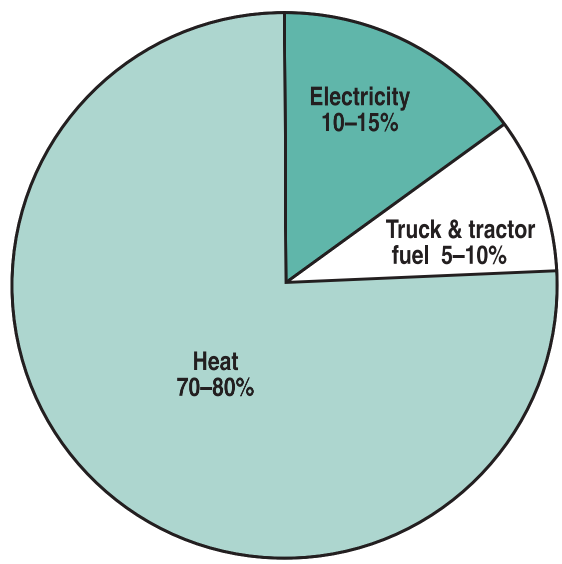


FIGURE 1a. Typical annual energy dollars spent in a commercial greenhouse operation

1 Principles of Heat Loss

The Basics of Heat Loss

The sun's energy is transmitted to the earth in the form of short-wave radiation (approximately 280–2,800 nanometers). When it passes through greenhouse glazing and strikes objects in the greenhouse, it is converted to heat. The glass or plastic traps the heat just like a layer of clouds. At night, supplemental heat is needed, because the glazing has little resistance to the outward flow of heat.

Heat loss from a greenhouse usually occurs via three modes of heat transfer: conduction, convection, and radiation. A fourth method is infiltration by air exchange through holes or cracks in the greenhouse shell. A fifth method is perimeter heat loss through the foundation. Usually, many types of heat exchange occur simultaneously (figure 1-1). The heat demand for a greenhouse is normally calculated by combining the first three types of heat loss as a coefficient in a heat loss equation and adding the infiltration to this total.

Conduction

Heat is conducted either through a substance or between objects by direct physical contact of the objects. The rate of conduction between two objects depends on the area, path length, temperature difference, and physical properties of the substance(s), such as density and conductivity. Except for path length, the greater any of these factors are, the greater the heat exchange.

Heat transfer by conduction is most easily reduced by replacing a mate-

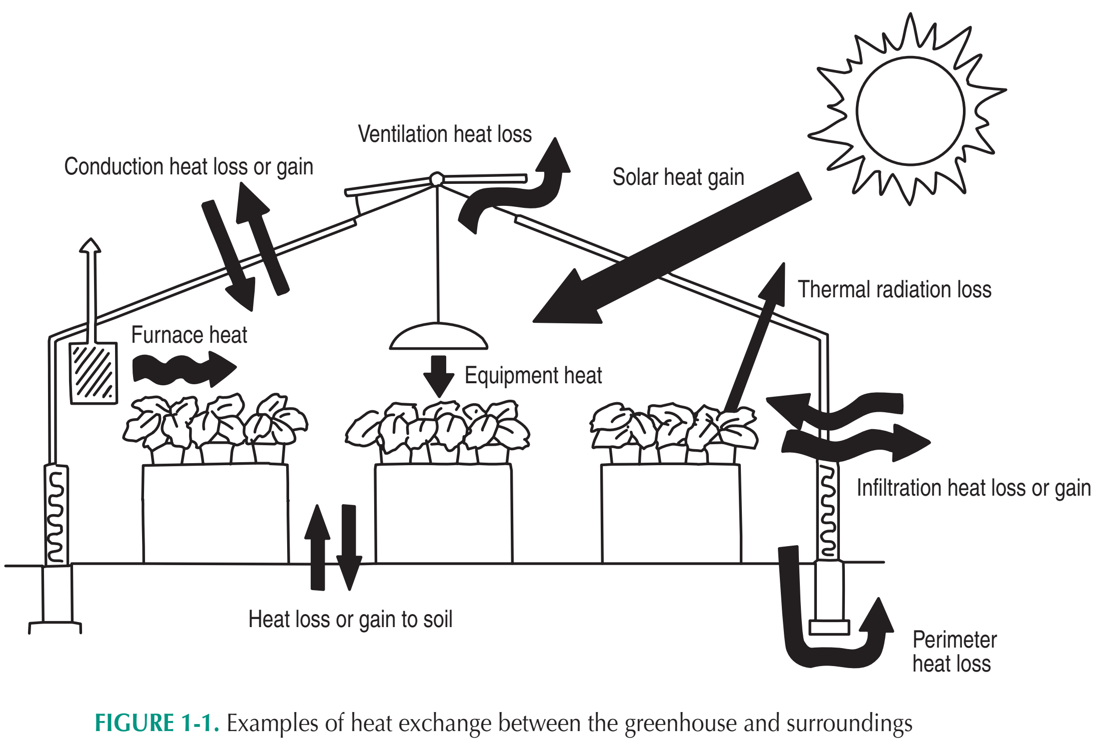


FIGURE 1-1. Examples of heat exchange between the greenhouse and surroundings

rial that conducts heat rapidly with a poor thermal conductor (insulator) or by placing an insulator in the heat flow path. An example of this would be replacing the metal handle of a kitchen pan with a wooden handle or insulating the metal handle by covering it with wood.

Air is a very poor heat conductor. Double-layered glazing materials reduce heat loss by forming an insulating air space. Likewise, fiberglass batts and foam insulating materials depend on trapped air for insulation effectiveness.

Convection

Convection is the exchange of heat between a moving fluid, such as air, and a solid surface. Inside the greenhouse, heat loss by convection occurs when warm air transfers its heat to the cold surfaces of the glazing and structure. This cooled air falls to the floor and is replaced by warmer rising air. The cool air has to be reheated to maintain greenhouse temperature. Meanwhile, the warmed greenhouse surfaces now conduct heat outside.

Heat transfer by convection includes not only the movement of air but also the movement of water vapor. When water in the greenhouse evaporates, it absorbs energy and reduces surrounding air and surface temperatures. When water vapor condenses to form a liquid, it releases energy. Thus, when water vapor condenses on the roof, it releases energy, some of which is conducted outside. A significant amount of heat is needed to evaporate the moisture from the plants, benches, and floor. It takes the same amount of heat to evaporate 1 gallon of water as to heat 1,000 gallons of water by 1°F.

Radiation

Radiation heat transfer occurs between two bodies without direct contact or an intervening transporting medium such as air. Like light, heat radiation follows a straight line and is either reflected, transmitted, or absorbed upon striking an object. Radiant energy must be absorbed to be converted to heat.

All objects radiate energy in numerous directions but vary in their capacity to absorb and emit radiation. The rate of radiation heat transfer varies with the area of an object, the difference of the temperatures raised to the fourth power, and surface characteristics of the two bodies involved. Generally, highly reflective, metallic surfaces reduce the amount of energy transferred by radiation. Dark or black surfaces usually absorb energy and then reradiate it to another surface.

Radiant heat loss from an object can be reduced by surrounding the object with a highly reflective, opaque barrier, which (1) reflects the radiant energy back to its source; (2) absorbs very little radiation, so it does not heat up and reradiate energy to other objects; and (3) prevents objects from "seeing" each other, a necessary element for radiant energy exchange.

Infiltration

Infiltration is the exchange of interior and exterior air. The rate of infiltration depends upon wind velocity and the amount of small openings in the building shell. Laps in glazing, openings under doors and louvers, or vents that don't close tightly allow such an exchange (figure 1-2). Infiltration air requires additional heat and can cause cold drafts on plants.

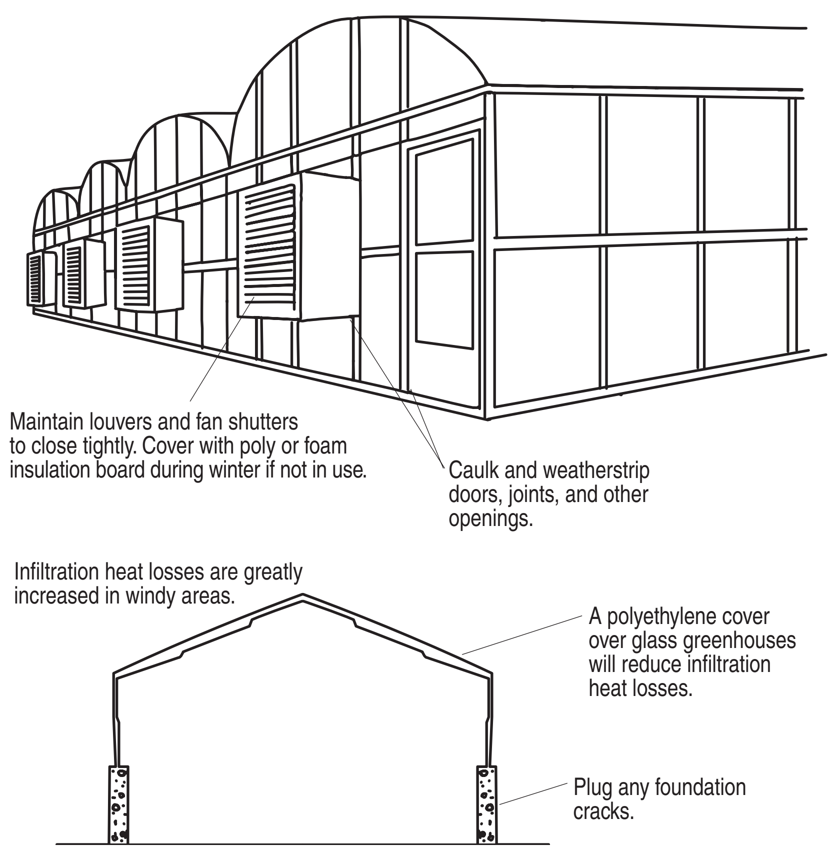


FIGURE 1-2. Heat loss by infiltration

A $1/8$-inch-wide crack around a 3-foot-wide entrance door will allow about 500 cubic feet per minute of air to infiltrate and require about 25,000 Btu's per hour of additional heat. If fuel oil costs $1.20 per gallon, the cost is about $0.30 per hour.

Wind reduces the thickness of an insulating film of air near the outside glazing surface, which has a minor effect on heat loss.

Factors Affecting Heat Loss

Solar radiation, infrared (IR) radiation, and light enter a greenhouse and are absorbed by plants, soil, and greenhouse fixtures. The warm objects then reradiate this energy outward. The amount of radiant heat loss depends on the type of glazing, ambient temperature, and amount of cloud cover. Rigid plastic and glass materials exhibit the "greenhouse effect," because they allow less than 4% of thermal radiation (heat) to pass through (figure 1-3).

In contrast, more than 50% of thermal radiation will pass through a single layer of polyethylene. A small amount of condensation on the polyethylene can reduce this thermal transmittance to 50%, and heavy condensation can reduce it to 25%. But condensation also reduces light levels at the plants and the amount of solar radiation entering the greenhouse. Thus, it is more important to keep glazed surfaces clear of condensation. In northern latitudes, greenhouse roofs should be sloped with a 6-in-12 pitch (6-inch rise in 12-inch horizontal) to allow condensation to run off.

IR-absorbent materials added to polyethylene have reduced energy losses from greenhouses by up to

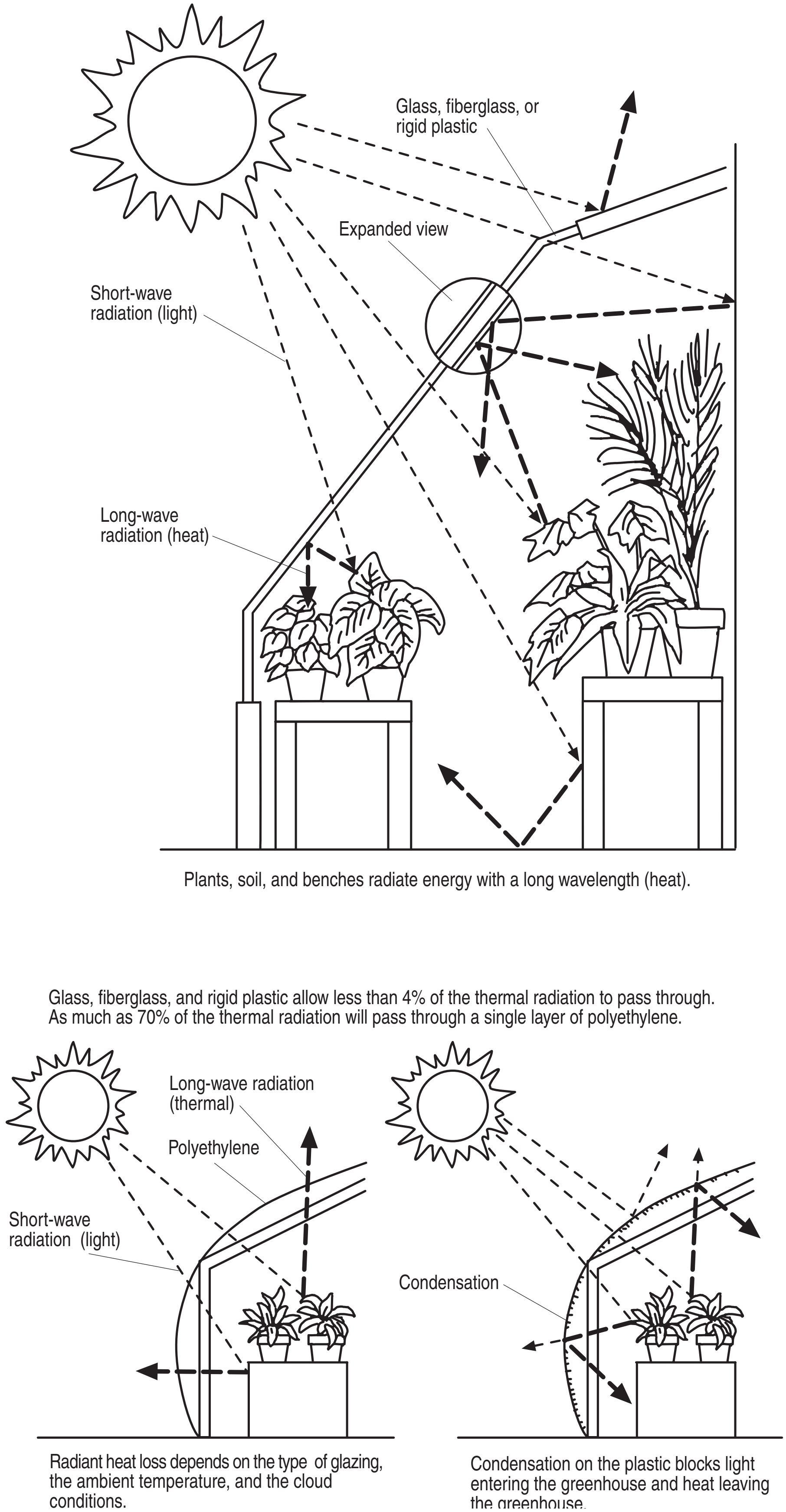


FIGURE 1-3. Radiant heat loss in a greenhouse

20% without lowering light transmission. Presently, IR greenhouse film costs only $0.01 more per square foot than regular three- to four-year greenhouse-grade film. At a 15% energy savings, the payback for installation of IR film would be only a few months in northern climates. Only one layer is needed, and it should be located as the inner layer in a double-layer, air-inflated covering. This traps the heat within the greenhouse. Many IR films also have an anticondensation additive, which should be on the inner layer to allow the moisture to drain off rather than drip.

Small greenhouses have more surface area relative to the floor area and are therefore more expensive to heat. Keeping the outside exposed surface area to a minimum reduces the greenhouse heat requirement per square foot of floor area. For instance, a range with six individual freestanding greenhouses, each 30 feet by 100 feet with 10-foot-high sidewalls, has a 37% greater surface area than a gutter-connected house providing the same floor area for growing. Multispan, gutter-connected greenhouses can be divided into heating zones with clear dividing walls. This division allows a more centralized operation, a single convenient headhouse, and reduced labor and energy costs (table 1-1).

Make sidewalls high enough to give adequate headroom. Adding a foot or two of sidewall height increases heat loss only by approximately 5%. Although heat loss is important, many growers, particularly those who grow hanging baskets, complain of lack of headroom. High sidewalls also give better clearance for thermal blankets and greater volume to buffer air temperature. Most gutter-connected greenhouses are now built with 12-foot- to 18-foot-high sidewalls.

The rate of heat loss by air infiltration depends on the age, condition, and type of greenhouse. Even glass greenhouses in good condition allow air to come through the edges of the glass panes. Greenhouses that are older or in poor condition generally have cracked, slipping, or missing glass through which large amounts of cold air may enter. Greenhouses covered with large sheets of plastic glazing, large glass panes, or a single or double layer of rigid or flexible plastic have significantly less infiltration.

The greenhouse ventilation system also has a large effect on infiltration. Inlet and fan shutters often allow a large air exchange if they don't close tightly due to poor design, dirt, damage, ice formation, or lack of lubrication. Window vents seal better than inlet shutters, but even they require maintenance to ensure a tight seal when closed. The newer hinged-roof greenhouses with full-length

TABLE 1-1. Typical heat loss area to floor area ratios for common greenhouse shapes

Greenhouse shape	Practical glazing	Example floor dimensions and area	Heat loss area (square feet)	Ratio: heat loss area to floor area[a]
Gable frame	All types	30 feet x 100 feet = 3,000 square feet (7-foot walls, 26˚ roof slope)	5,380	1.8
A-frame and pit	All types	30 feet x 100 feet = 3,000 square feet	4,700	1.6
Quonset	Fiberglass Polyethylene Flexible polycarbonate	30 feet x 100 feet = 3,000 square feet	5,000	1.7
Gothic	Fiberglass Polyethylene Flexible polycarbonate	30 feet x 100 feet = 3,000 square feet	5,450	1.8
Brace (solar design)	All types	30 feet x 100 feet = 3,000 square feet	about 3,000	1.0
Multispan	All types	126 feet x 200 feet = 25,200 square feet (14-foot walls)	38,030	1.5
Multispan	All types	For areas greater than 1 acre	Approaches 1.0	
Lean-to	All types	15 feet x 100 feet = 1,500 square feet	2,200	1.5

Note: Heat loss area = Area of roof + Wall glazing

[a] The lower the ratio, the less the heat loss

vents need to be checked before winter to ensure that there are no large gaps when they close.

Heat Loss Calculations

Transmission heat loss may be estimated by the equation:

$Q = U \times A \times \Delta T$

Where:

- Q = Transmission heat loss, Btu/hour
- U = A heat transfer coefficient, Btu/hour-square foot-˚F
- A = Area of greenhouse surface, square feet
- ΔT = Air temperature difference between inside and outside, ˚F

This equation assumes no solar gain and is often used to calculate the amount of heat required to keep the greenhouse at a desired temperature under the most adverse heating conditions. This value is then used to determine the heat delivery requirement of the greenhouse heating system in horsepower or Btu/hour.

Sometimes R values (the resistance to heat flow) are listed instead of U values. The relationship between U and R is: $U = 1/R$

Frequently, it is more convenient to work with R values when dealing with insulation, as the insulation effect can be determined quickly by simply adding the R values of materials in the heat flow path. U values cannot be added together. Table 1-2 lists the U values and R values of different materials commonly used in greenhouse construction.

Note that high R values and low U values indicate less heat flow. Absorption of water into a building material will reduce the R value and increase heat loss. Vapor barriers must protect materials that are permeable to water vapor. Always install a vapor barrier towards the warmer (more moist) side of the structure. This is usually the inside.

Air infiltration heat loss should be added to transmission heat loss. The equation for infiltration heat transfer is:

$Q = 0.02 \times V \times C \times \Delta T$

Where:

- Q = Infiltration heat loss, Btu/hour
- V = Greenhouse volume, cubic feet
- C = Number of air changes per hour
- ΔT = Air temperature difference between inside and outside, ˚F

Table 1-3 lists air infiltration through various types of greenhouses. The number of air exchanges per hour will vary depending on the type and condition of the greenhouse and the velocity of the wind.

Heat is also lost to the ground underneath and beside a greenhouse. The perimeter heat loss around the foundation may be added to other losses using table 1-2 and the equation:

$Q = P \times L \times \Delta T$

Where:

- Q = Perimeter heat loss, Btu/hour
- P = Perimeter heat loss coefficient, Btu/hour-linear foot-˚F (see table 1-2)
- L = Distance around perimeter, feet
- ΔT = Air temperature difference between inside and outside, ˚F

Appendix B (page 74) shows how to calculate heat loss from a typical greenhouse.

TABLE 1-2. Heat flow through various construction materials

Insulation materials	U value (Btu/hour-square foot-˚F)	R value (˚F-square foot-hour/Btu)
Glass fiber board, 1 inch	0.25	4.0
Expanded polystyrene, 1 inch, cut surfaces	0.25	4.0
Expanded polystyrene, 1 inch, smooth-skin surface	0.20	5.0
Expanded polystyrene, molded beads, 1 inch	0.28	3.6
Expanded polyurethane, 1 inch	0.16	6.2
Vermiculite, 1 inch	0.45	2.2
Glass fiber blanket, 3.0–3 1/2 inches	0.09	11.0
Glass fiber blanket, 5.0–6 1/2 inches	0.05	19.0
Roof and wall glazing		
Glass, single layer	1.1	0.91
Glass, double layer, 1/4-inch space	0.7	1.42
Glass, triple layer, 1/4-inch space	0.5	2.00
Polyethylene or other film, single layer	1.1	0.91
Polyethylene or other film, double layer, separated	0.7	1.42
Polyethylene film, double layer, separated, IR-inhibited	0.5	2.00
Polyethylene or other film, double layer, separated, over glass	0.6	1.67
Fiberglass-reinforced plastic, corrugated sheet	1.0	1.00
Single polycarbonate, corrugated sheet	<1.14	<0.91
Double acrylic or polycarbonate, 8 millimeter	0.6	1.67
Triple polycarbonate, 8 millimeter	0.5	2.00
Wall materials		
Concrete block, 8 inches	0.5	2.00
Concrete block, 8 inches with 2 inches foamed polystyrene	0.1	10.0
Plywood, 1/2 inch	0.7	1.42
Concrete, poured, 6 inches	0.8	1.25
Concrete block or plywood, plus 1 inch foamed urethane	0.13	7.69
or plus 1 inch polystyrene beads	0.2	5.00
Cement/mineral fiberboard, 1/2 inch	1.1	0.91
Cement/mineral fiberboard, 1/2 inch with 2 inches foamed polystyrene	0.1	10.0
Expanded polystyrene, 1 1/2 inches, aluminum skin both sides	0.12	8.33
Greenhouse with thin thermal blanket [a]	0.3–0.7	1.42–3.33
Perimeter	**Perimeter heat loss coefficient (Btu/hour-linear foot-˚F)**	
Uninsulated	0.8	1.25
Insulated with 2 inches foamed polystyrene extending 24 inches into the ground	0.4	2.5

Note: High R values and low U values indicate less heat flow. Absorption of water into a building material will reduce the R value and increase heat loss. Vapor barriers must protect materials that are permeable to water vapor. Always install a vapor barrier towards the warmer (more moist) side of the structure.

[a] Table 4-1 (page 20) lists U factors (heat loss) for specific thermal blankets. Values will be slightly higher in a loose house, which has high infiltration losses. Values are based on outside greenhouse surface area.

TABLE 1-3. Natural air exchanges (infiltration) for greenhouses

Construction system	Air exchanges per hour [a]
New construction: glass, fiberglass, polycarbonate, or acrylic sheets	0.75–1.5
New construction: double-layer plastic film	0.5–1.0
Old construction: glass, good condition	1.0–2.0
Old construction: glass, poor condition	2.0–4.0

[a] The number of air exchanges per hour will vary depending on the type and condition of the greenhouse and the velocity of the wind. Low wind or protection from wind reduces air exchange.

2 Greenhouse Site Selection and Modification

Windbreaks

Wind velocity increases the rate of natural air exchange (infiltration) through leaks in the structure. In comparison to still air, a 15-mile-per-hour wind can double the heat loss from a single-glazed glass structure. Also, wind reduces the thickness and effective insulation value of the thin film of still air along the greenhouse glazing.

Any properly designed obstruction that decreases wind velocity, such as a wall, a fence, a building, trees, or a hill, can act as an effective windbreak to cut heat loss 5–10% below that in an open area. Windbreaks also reduce the risk of structural damage from heavy windstorms, and, by reducing infiltration, they increase the effectiveness of carbon dioxide enrichment used to improve plant growth.

The extent of downwind protection is related to the height, length, and porosity of the windbreak. A solid barrier is not as effective as a porous one, because it creates turbulent downdrafts behind the barrier. A porous barrier reduces the downstream vacuum and improves windbreak effectiveness. Research has shown that a windbreak that is 50–60% open is optimal.

A well-planned windbreak of trees placed upwind of the prevailing winter winds will reduce wind velocities for ten to thirty tree heights downwind. During construction of the greenhouse, natural windbreaks should be protected, as it takes a long time to establish a new one. A tree windbreak is inexpensive, long-lived, and requires little maintenance.

Establishing a Windbreak

To construct a tree windbreak, first sketch the present greenhouse layout (allowing for future expansion). To avoid light interference, plant trees no closer to the greenhouse than four times the expected mature tree height. The best zone of protection is four to six mature tree heights downwind from the windbreak, where the wind force is to be broken by approximately 50% (figure 2-1).

The most effective windbreak consists of four to five rows of a mixture of deciduous and evergreen coniferous trees planted perpendicular to the normal winter prevailing wind. Tree rows should be at least 50 feet longer than the greenhouse on each end, as the buffering effect increases the wind velocity by 10–20% at the ends of the windbreaks. Planting different kinds of trees guards against losing an entire planting to insects or disease and makes a rough surface for a more effective windbreak.

For a fence-type windbreak, use commercial snow fence mounted two levels high, 1-inch-thick boards, or woven polypropylene netting designed for windbreaks. The fence should be open or 50–60% porous for best results. Fences with openings wider than 6 inches will be ineffective.

A 10- to 12-foot-high fence placed 40–60 feet away will give good wind protection to a typical greenhouse with an 11- to 14-foot-high ridge. Posts (6-inch-by-6-inch-square posts or 6-inch-top-diameter poles) spaced 10 feet apart and set 4 feet into the ground will support the fence.

Benefits and Costs

Although windbreaks are effective with any greenhouse, greatest savings are realized in open, high-wind areas or with older, leaky greenhouses. The cost of establishing a windbreak will vary. A well-fertilized and irrigated tree windbreak will produce effects in five years. Fences are more expensive but immediately effective. A combination of a fence windbreak in front of trees would give early protection until the trees reach an effective size.

The windbreak should not shade the growing area. Trees cast a shadow twice their height in the winter. Normally, a northern or northwestern windbreak will reduce solar radiation very little in the greenhouse. Windbreaks also act like a snow fence, so exercise care in snow regions to avoid drifts in access roads or in front of auxiliary buildings.

Orientation

Greenhouses are normally oriented so that maximum solar radiation may enter. In northern latitudes, orientation is one of the most important physical aspects controlling the amount of light entering a greenhouse. Local customs, construction techniques, and degree of cloud cover enter into decisions about greenhouse orientation.

In northern areas of the United States (above 40 degrees latitude), single-span greenhouses are usually built with the ridge running east-to-west to receive maximum light in the winter (the most critical season for light), late fall, and early spring. During this period, in most northern latitudes, total light for an average day is approximately one-quarter of that available in June. A freestanding greenhouse collects the most radiation over the entire year when the long dimension is oriented north-to-south, but winter light is the major factor to be concerned with.

Multispan, gutter-connected greenhouses are almost always constructed with the gutters oriented north-to-south. This orientation allows the shadow from the gutter to move from west to east across each bay during the day. If the gutters were oriented in a true east-to-west direction, some areas would be continuously shaded. Multispan greenhouses with gutters should have ventilation fans on the north wall and ventilation inlets on the south wall. When evaporative pads are to be installed (see figure 6-6, page 44), the fans and vents should be reversed to reduce shading.

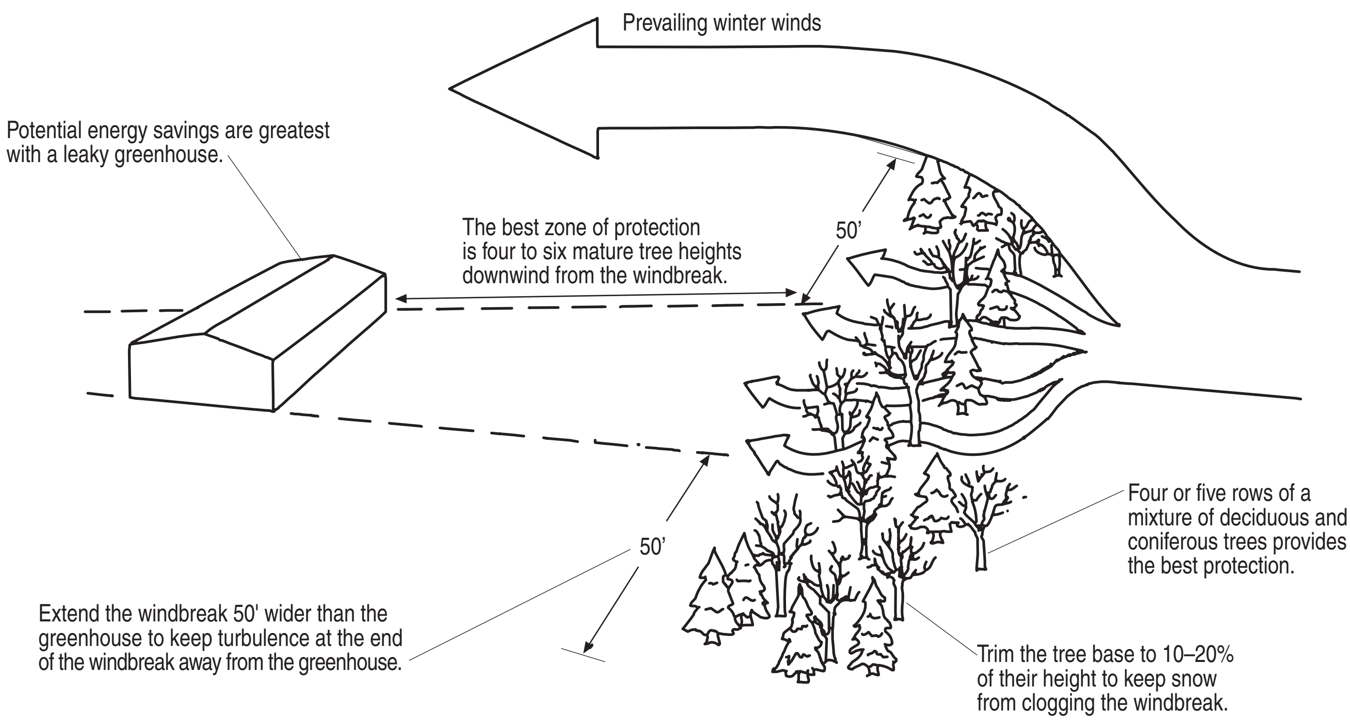


FIGURE 2-1. Windbreaks offer protection from prevailing winter winds

3 Construction Materials

Frame Materials

Aluminum, galvanized steel, and wood are common frame and bench materials. Most heat is lost through the glazing by conduction, not via the frame.

Wood—pressure-treated with a preservative such as chromated copper arsenate (CCA), ammoniacal copper arsenate (ACA), ammoniacal copper zinc arsenate (ACZA), or other preservative containing a combination of copper, chromium, and arsenic—is suitable for greenhouses. **Do not use creosote- or pentachlorophenol-treated wood.** These preservatives release vapors harmful to plants, unless they are completely covered with a sealing paint. Paint all wood framing white to improve the appearance of the greenhouse and increase light reflectivity.

Aluminum and galvanized steel require little maintenance. Commercial manufacturers use both aluminum and steel for greenhouse structures. Aluminum may be extruded to form special shapes. It is commonly used for glazing bars, bar caps, and glazing attachment extrusions (figure 3-1). Galvanized steel has the advantages of strength and modest cost, but it is subject to long-term corrosion, particularly inside steel tubing and piping supports. It should be galvanized after cutting and drilling to coat all surfaces.

Foundations

Concrete makes a good permanent foundation. It should be insulated when placed above ground. Concrete blocks may make less expensive walls than poured concrete, but these, too, should be insulated. Pressure-treated wood posts with treated plywood panels also make good greenhouse foundation walls.

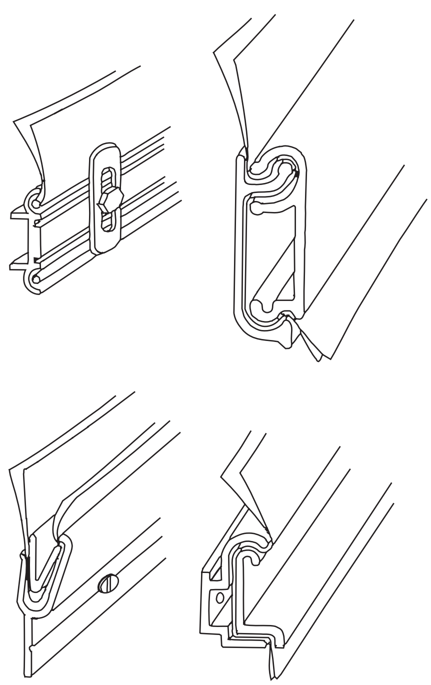


FIGURE 3-1. Aluminum extrusions for attaching film plastic

Most hoophouses use galvanized steel tubing driven into the ground as support. Posts are tied together with pressure-treated lumber, which also provides an anchor for the plastic. Board-type insulation may be placed between the posts and buried into the ground up to 24 inches (see figure 4-1, page 14). Gutter-connected greenhouses use galvanized steel tubing encased in a concrete pier for support. Space between posts in the exterior wall is usually filled with an insulating panel. Foundations and piers should be placed to below the frost line to prevent heaving.

Glazing

Many translucent and transparent glazing materials are available in both single or double configurations. These include glass, corrugated and flat fiberglass-reinforced plastic panels, corrugated polycarbonate, double-walled acrylic and polycarbonate panels, and acrylic-coated polycarbonate panels. Polyethylene, polyvinyl chloride, and polyester are manufactured as films.

The selection of glazing materials for greenhouse modification or for a new structure depends on cost, expected life, handling and installation requirements, radiation transmittance, and crop growth. Since energy conservation is a major consideration, many northern greenhouses have double glazing. Double polyethylene inflated film and polycarbonate panels are most popular. Studies made of the double covering systems indicate they all have about the same heat loss properties. They usually save about 35% over a single glazing. Variations in heat loss are probably the result of mounting techniques, the presence of thermal breaks, and the width of the air space between the two layers.

Glazing materials vary in their abilities to transmit thermal energy (long-wave radiation, greater than 2,800 nanometers). A comparison of many materials is shown in table 3-1 (page 12). Polyethylene film is transparent to long-wave radiation and on clear nights will transmit more energy than other glazing materials. Film with a long-wave radiation inhibitor is available and should be placed as the inner layer in a double-glazed system. Condensation reduces radiant heat loss and light transmission and causes most glazing materials to act similarly in the typical greenhouse.

Since glazing materials are of similar thicknesses, only the surface conditions govern the heat transfer through each glazing surface. Almost all single-layer materials have a heat transfer, or U factor, of 1.0–1.2 Btu/hour-square foot-°F, and double-walled materials are between 0.6 and 0.7 Btu/hour-square foot-°F.

Heat loss by infiltration depends on the physical characteristics of the glazing material and condition of the greenhouse. Film materials have the least infiltration loss; single, small panes of glass with lap joints exhibit the greatest. Heat loss from double-glazed structures is less influenced by wind, since only the outside surface is affected. The method of attachment makes the glazing less subject to infiltration losses as well.

Light transmission is an important consideration for crop production. Single-glazed glass structures with large glass panes and few supports retain their popularity because they transmit light. Interior movable insulating blankets are often used to offset the significantly higher heating costs for single glazing. Studies of energy-conserving blankets indicate a variety of effects on cropping time, flower production, weight, and stem length based on the type of crop grown and covering materials used. For more information on blankets, see chapter 4.

Other considerations in evaluating glazing materials include maintenance (for example, polyethylene film needs to be replaced every three to four years), flammability, and discoloration of the material. When reglazing or remodeling a greenhouse, the structure may require alteration to hold a new material.

TABLE 3-1. Comparison of glazing materials

General type	Transmittance			Estimated life (years)
	Visible light (%)	UV light (%)	IR light (%)	
GLASS				
Advantages				
Excellent transmissivity • Superior resistance to heat, UV, and abrasion • Low thermal expansion/contraction • Readily available • Transparent				
Disadvantages				
Difficult to fabricate on-site • Low impact resistance unless tempered • Expensive • Heavy				
Material				
Single/clear/float/$^{1}/_{8}$-inch	88	80	<3	25+
Single/clear/tempered	90	70	<3	25+
Single/clear/low-iron/tempered	93	n.a	<3	25+
Single/bronze/tempered	68	39	<3	25+
Double/clear/tempered	82	52	<3	25+
Double/clear/tempered/low-iron	86	n.a.	<3	25+
Double/clear/tempered/low-E	78	32	<3	25+
ACRYLIC				
Advantages				
Excellent transmissivity • Superior UV and weather resistance • Lightweight • Easy to fabricate on-site				
Disadvantages				
Easily scratched • High expansion/contraction • Slight embrittlement with age • Expensive • Relatively low service temperatures • Flammable				
Material				
Single/clear/8mm	93	n.a.	<5	20+
Double/clear/8mm	86	44	<5	20+
POLYCARBONATE				
Advantages				
Excellent service temperatures • High impact resistance, hail proof • Low flammability • Lightweight • Can bend over curved surfaces				
Disadvantages				
Easily scratched • High expansion/contraction				
Material				
Single/clear/corrugated	90	0	<3	10–15
Single/white	42	0	<3	10–15
Double/clear/8mm	83	18	<23	10–20
FIBERGLASS-REINFORCED PLASTIC				
Advantages				
Inexpensive • Strong • Superior weatherability if Tedlar-coated • Easy to fabricate and install on-site				
Disadvantages				
Susceptible to UV, dust, pollution • Yellows with age • High expansion/contraction				
Material				
Single/clear/corrugated or flat	89	19	<3	10–15
Double/clear/flat	85	n.a.	<3	7–12
POLYETHYLENE FILM				
Advantages				
Inexpensive • Easy to install • Readily available in large sheets to 52 feet wide				
Disadvantages				
Short life • Low service temperature				
Material				
Single/ag-grade/clear/6-mil	87	60	50	1
Single/greenhouse-grade/clear/6-mil	87	60	50	3-4
Single/greenhouse-grade/white/4-mil	40	n.a.	n.a.	4-5
Double/greenhouse-grade/clear/6-mil	78	48	50	3-4

4 Insulation

Both light-transmitting and opaque insulation are used to reduce greenhouse heat loss. Opaque insulation is frequently used on north walls or along sidewalls up to plant height. Any insulation must be waterproof or protected from water with a vapor barrier. Opaque and reflective insulation also minimize radiant heat loss, but both types may reduce light levels in the greenhouse.

Opaque Insulation

Walls can be covered with opaque material from the foundation up to plant height. Rigid board insulation, such as extruded polystyrene, extruded polyurethane, or isocyanurate board, is a commonly used material. Polystyrene beadboard can absorb moisture and is not generally recommended for use in greenhouses. Extruded polystyrene and polyurethane boards are only slightly affected by water vapor, but they must be protected from deterioration due to sunlight and covered to reduce fire hazard. Some boards are covered with an aluminum foil laminate that protects them and reflects direct solar radiation back to the crop canopy.

Fiberglass insulation is best for the headhouse and packing house, where it can be protected from moisture with a vapor barrier. It is not recommended for use in the greenhouse.

Foundation Walls

An uninsulated 6-inch concrete foundation wall has an R value of 1.6. An inch of polystyrene (R=5.0) added to the wall increases the wall R value to 6.6 and reduces heat losses by 75%.

Insulation may be added to the outside or inside of a foundation. When insulation is placed outside:

- The wall becomes part of the mass of the building that stores solar heat and reduces greenhouse air temperature fluctuations.
- Problems of installing perimeter wall heat pipes are reduced.
- The insulation needs to be protected from mechanical and rodent damage.

Sprayed-on urethane insulation is an excellent wall insulator. It should extend at least 18 inches below grade. Insulation applied outside a wall must be completely weatherproofed (figure 4-1, page 14).

Inside insulation needs less weatherproofing, although protection from water and ultraviolet radiation from the sun is necessary if the material is exposed plastic foam. Reflective coatings of a board insulation should face inward but should not touch perimeter heating pipes. Extend the insulation to a convenient depth (12–24 inches) below the floor to block heat loss at the perimeter. For example, a 4-foot-wide insulation board insulates a 2-foot-high wall with 2 feet below grade.

North Wall Insulation

Rigid insulation board may be effectively applied to all foundation walls and other opaque surfaces on a greenhouse structure. The addition of more extensive north wall insulation is controversial. In cloudy climates, much of the light received by the crop is reflected from clouds and the surroundings. In these areas, a fixed opaque insulation on any glazing, including the north wall, reduces light levels, affects the crop quality, and may possibly delay flowering.

In sunny winter climates, reflective board insulation on the north wall will reduce heat loss up to 10%. A good compromise is to insulate the entire perimeter foundation and part way up the north wall (especially in small greenhouses).

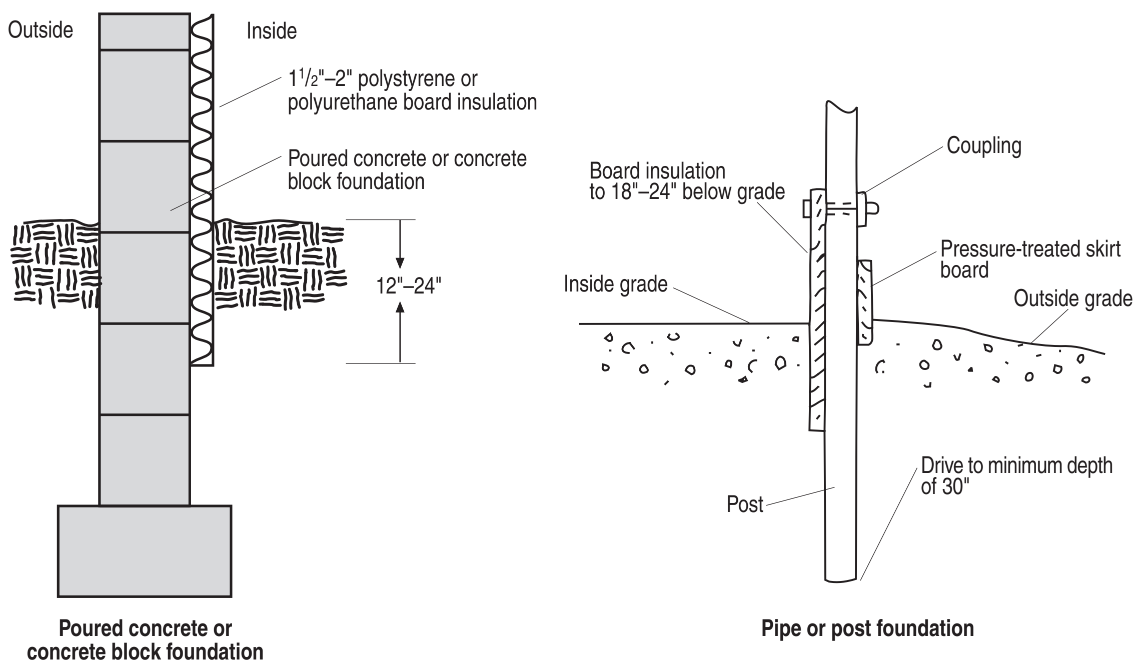


FIGURE 4-1. Perimeter insulation

Some growers have attempted to insulate the north roof in an east-west-oriented greenhouse with poor results. Research at Cornell University found that if the roof were insulated more than one-quarter of the way up from the eave, the rate of production decreased. In several Connecticut greenhouses, phototropism (the bending of a plant toward light) occurred when the north roof was insulated, even though the insulation was reflective.

Headhouse and Auxiliary Buildings

Insulate and tighten up auxiliary buildings such as packing areas, potting sheds, maintenance buildings, offices, and so forth, with fiberglass or other insulation. Protect this type of insulation from humidity with a vapor barrier on the winter warm side. Also, protect it from mechanical damage. Install weathertight storm doors, storm windows, or double glazing. Place insulation in all areas exposed to the exterior to reduce winter heat loss and prevent summer heat gain. Weatherstripping or caulking inserted in cracks decreases infiltration. Weatherstripping storm doors and storm windows in the office and sales area will prove energy-efficient, but storage spaces may not need such measures.

Insulate hot water and steam pipes that pass from the boiler or mechanical room to the greenhouse. Insulate along their entire route, unless they are designed to heat the headhouse. Often, headhouses are overheated or needlessly heated at night. Significant savings can be achieved by using standard pipe insulation on large mains going to the greenhouse.

Transparent Insulation

A tightly installed greenhouse covering reduces heat loss significantly. In addition, several transparent materials may be added to reduce infiltration in glass houses. Weatherstripping on doors and vents, good glass maintenance, closing gaps under the foundation, and lubricating ventilation louvers so they close tightly can reduce heat loss by 3–10%. Fans and intake louvers that are not operated during the winter should be enclosed with insulation.

Plastic bubble insulation is a composite of clear polyethylene that has been vacuum-formed to create air spaces in small bubbles. It is commonly used as a packaging material. Bubble insulation is difficult to attach inside the greenhouse, but it may be stapled directly to wooden sash bars. Double-sided tape has proven to be ineffective. Various estimates of light reduction have been suggested; one estimate suggests that bubble insulation transmits 12% less light than single window glass. It should not be placed on roofs where snow may overload the structure.

In older glass greenhouses, sealing the laps between the glass panes is effective to reduce infiltration (figure 4-2). A transparent silicone caulking compound works well. First, remove dirt and moisture from between the glass laps with compressed air. Sec-

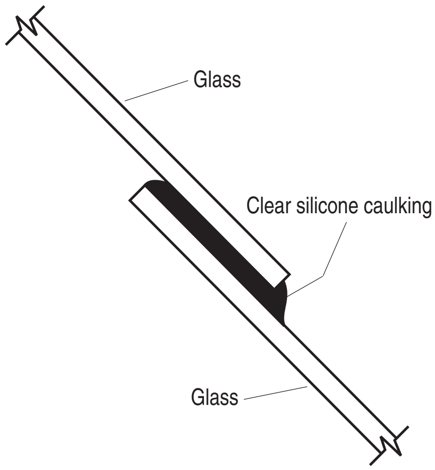


FIGURE 4-2. Reducing infiltration in glass greenhouses with caulking

ond, inject clear silicone-based sealant. This material readily adheres to clean glass and does not harden, so the seal is maintained during glass expansion and contraction and prevents glass slippage. This seal is permanent, because the sealant cannot be removed easily from the lap area. If the glass breaks, a special knife can be used to cut the sealant so the glass can be removed.

Replacing small glass panes with large tempered glass panels (30–36 inches wide) eliminates many air gaps at the laps and glazing bars. It also increases the light level, as there is less structural support.

Reducing infiltration by any method influences the carbon dioxide and humidity levels. A tighter greenhouse means less air exchange, so carbon dioxide levels may be rapidly depleted. In double-glazed structures, where heat loss is lower, the daytime ventilation requirement will normally supply enough carbon dioxide. Tight houses in cold climates with supplemental lighting do need supplemental carbon dioxide. Some additional ventilation may be required to alleviate excess condensation drip and related potential disease problems.

Polyethylene Film

Polyethylene film is a popular greenhouse glazing because of its low initial cost, high light transmission, and good energy-saving qualities. Besides its use as a standard glazing on a large percentage of greenhouses built today, it can be used to tighten up existing older glass greenhouses.

Double Polyethylene Over Glass

Using the air-separated technique, two layers of 4- or 6-mil greenhouse-grade polyethylene film are installed directly over a single-glazed structure, usually glass. The film lasts three to four years. A film with a one-year life could also be used if the greenhouse is to be covered only during the winter. Aluminum extrusions are available from greenhouse suppliers to securely attach the film and carry the loads imposed on the film by the air pressure used in the covering system. Figure 4-3 (page 16) illustrates several methods of installing double polyethylene over glass.

First-year commercial installation costs are about $0.50 per square foot. The costs for subsequent covering every third or fourth year is $0.10–$0.20 per square foot for material and labor. Re-covering large glass houses with film is difficult, but growers who have no other option have experienced energy savings of about 50%.

The system does reduce light transmission appreciably. In some cases, the lower light has been offset, because the extra insulation keeps night temperatures at the desired level. A single-glass house without the film covering may have temperatures that are too low. Also, because the house is tighter, it has less air exchange. This causes more rapid depletion of carbon dioxide and an increase in humidity. To overcome the approximate 18% loss in light level due to the film, some growers cover only the north roof and all endwalls and sidewalls and leave the south roof uncovered.

> **FLAMMABLE MATERIAL PRECAUTIONS**
>
> Some foam insulation is highly flammable. To reduce the fire hazard, cover insulation foam boards with 29-gauge galvanized steel, 0.032-inch aluminum, or a flame-retardant coating.
>
> Be careful when spraying urethane foam insulation in closed and confined areas. Gases produced in the foaming process are toxic to plants and dangerous to humans. Protect the foam to reduce fire hazard and prevent sun degradation.
>
> Foamed urethane has been applied successfully to the underside of steel gutters in gutter-con nected houses. It enables mod est heat savings and reduces troublesome condensation drip under the gutter. Insulating the gutter too heavily, however, can cause ice and snow buildup in the gutters. In such cases, consider attaching a steam or hot water pipe inside the gutter to melt ice and snow during storms. A line of heat pipes supported a couple of feet to each side of the gutter under the glazing is a more effective way to melt snow that collects on the roof above the gutter. These lines should be controlled with manual valves and operated only when needed.

No snow load problems should occur with inflated polyethylene over glass. A significant snow load will collapse the poly onto the glass to increase the melting rate. Light snow will remain on the roof longer and cause some winter light loss.

Observe these precautions when installing double polyethylene on a greenhouse:

- Keep spans of film to 20 feet or less to keep the film stress within reasonable limits and reduce the chance for failure.
- Attach the devices that secure the plastic to the greenhouse with bolts passing through structural members. Smooth or cushion all sharp edges to prevent puncturing the plastic.
- Maintain the internal pressure between the two layers at 0.25 inch of water by controlling the air inlet to the inflation blower with a metal plate or round electrical outlet box cover. The pressure can be measured with a manometer with one tube placed between the layers and the other outside of the plastic (figure 4-4).
- Supply outside air to the blower to reduce condensation between the plastic layers.
- Be careful when working on the glass roof, and use scaffolding designed for glass maintenance.
- Patch holes in the plastic to keep the inflation pressure constant. Large sections of plastic blown loose during very windy conditions can cause extensive breakage.
- Be prepared to adapt management to respond to the warmer and more humid growing environment that will result.

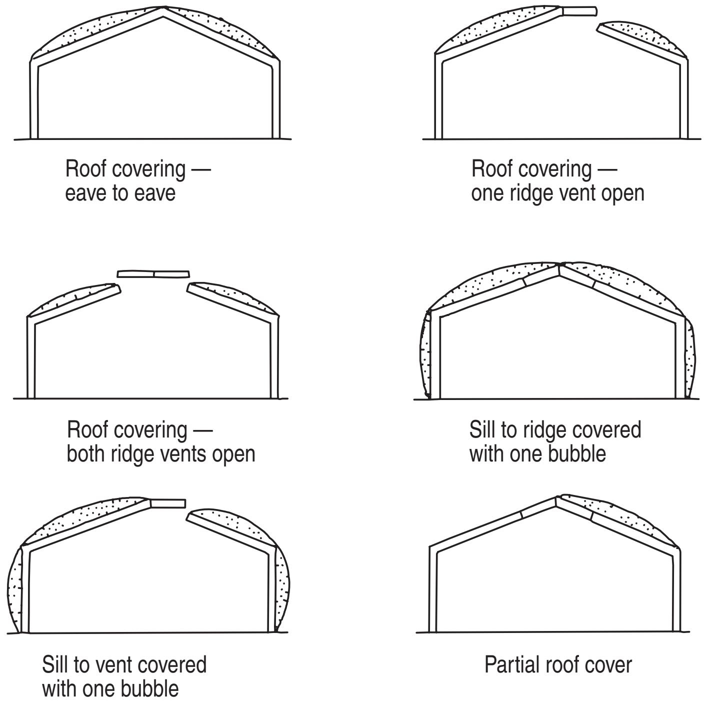


FIGURE 4-3. Typical methods of applying a double polyethylene cover over glass

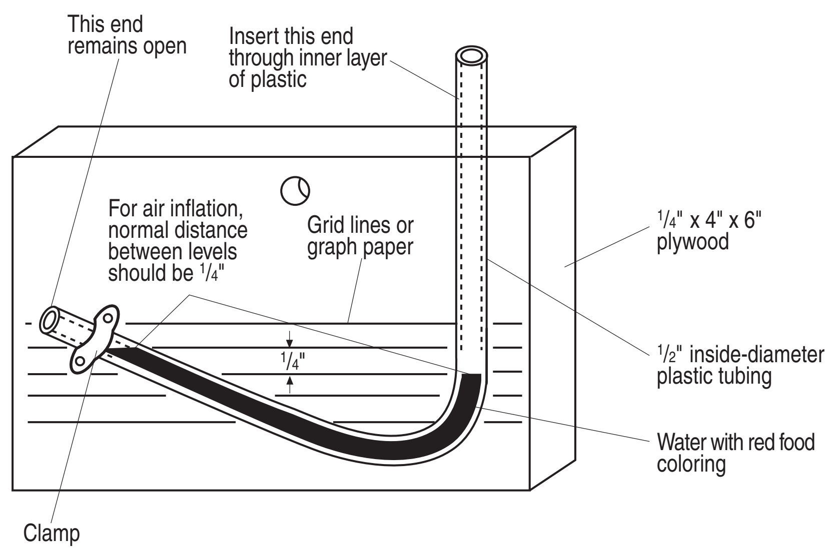


FIGURE 4-4. Homemade manometer for measuring static pressure

Single Polyethylene Over Glass

A single-layer polyethylene cover over glass maintains higher light levels and better production than double poly over glass. It has about the same heat loss as the double poly over glass if an air space is maintained. The film may be attached to the structure with aluminum extrusions or wooden furring strips. When lap seal has been applied to the greenhouse, a single-layer film may be inflated with the benefits of double-film glazing. Figure 4-5 shows another method of holding a single film rigid over glass to provide an insulating air film.

Costs for the single layer are similar to that of the double layer, except only one layer of film needs to be purchased. Glass houses in poor repair require about 40% less energy when they are covered with a single layer of polyethylene.

Fixed Clear-Film Ceiling

A fixed, horizontal polyethylene film ceiling or interior lining has been applied to glass houses with varying degrees of success. An interior ceiling is generally not recommended, as it reflects some sunlight entering the greenhouse. It also collects condensation or rain water from roof leaks; the resulting puddles will destroy the ceiling if they are not removed.

In some areas, snow loading will be a problem, and growers who use this system must cut the plastic film during heavy snow falls or circulate heated air into the attic space. In any event, check with the insurance company before installing any inside fixed-roof insulation system.

Some growers in warmer areas have used polyethylene ceilings effectively for crops with low light requirements. Polyethylene-lined walls generally work well to reduce infiltration in glass houses.

Movable Nighttime Insulation

Research indicates that, in many areas of the United States, 80% of the energy for heating single-glazed structures is required at night. In double-glazed structures, the night heating percentage is higher.

This observation suggests that insulation systems have their greatest benefit at night and should be designed so as not to block light during the day. Movable blanket or thermal screen systems will fulfill both objectives. Blankets can also control daylength, shade crops, and reduce day temperatures. These systems have shown a high return on investment.

Support and Drive Systems

The thin, flexible blanket is supported and moved by various methods to form a ceiling. Figures 4-6, 4-7 (page 18), and 4-8 (page 18) illustrate typical installations in freestanding and gutter-connected greenhouses. Horizontal blankets running gutter-to-gutter or truss-to-truss are more effective than those that follow the contour of the roof. This is due to less surface area (about equal to the floor area) for the heat to escape.

The thermal blanket may be sup-

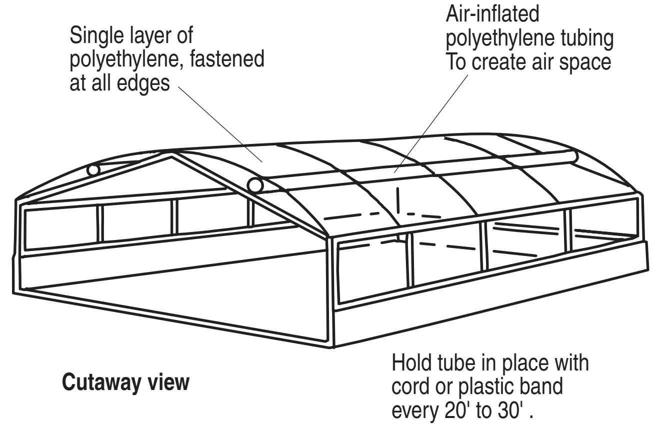


FIGURE 4-5. Method of covering a glass greenhouse with single polyethylene

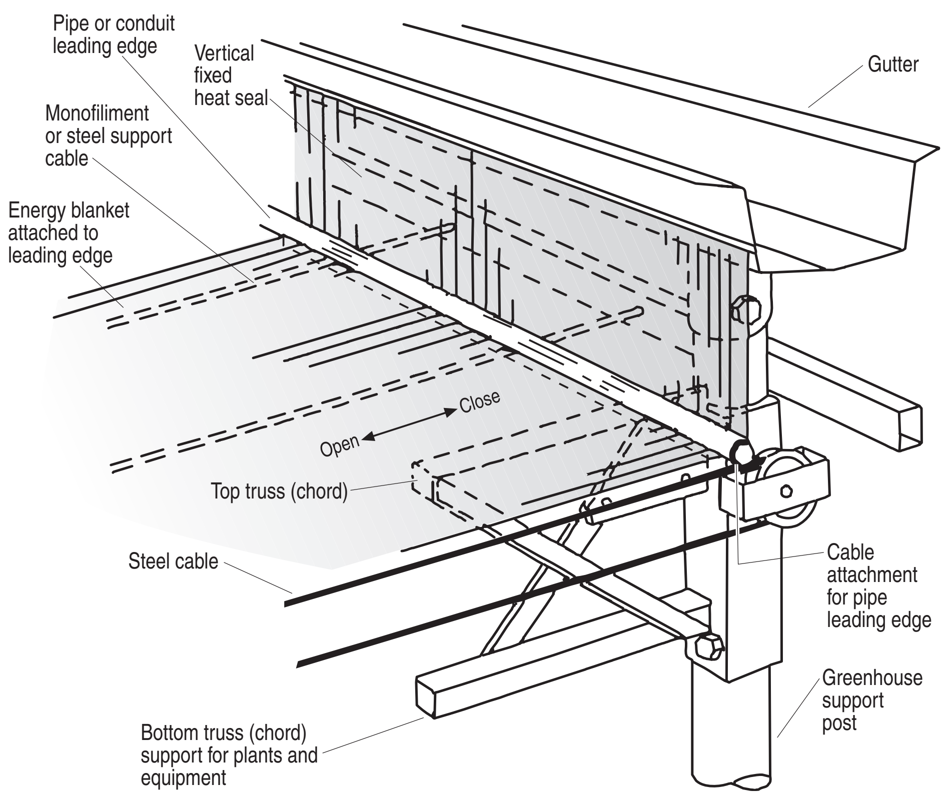


FIGURE 4-6. Cable-supported blanket system for gutter-connected greenhouse

ported by sliding carriers that hook into the material or by a network of monofilament lines spaced on 18- to 24-inch centers beneath the blanket. A leading edge of pipe, conduit, or aluminum extrusion connected to a drive cable or other system draws the material across the greenhouse at night. Figure 4-6 (page 17) illustrates a system where the material slides on monofilaments and shows a clear-span, energy-saving truss located below the gutter that may be used to support hanging baskets, hanging crops, heating pipe, and so on. Figure 4-7 shows a system that folds the film in accordion fashion on the north wall to reduce shading during the day. Figure 4-8 depicts an aluminum track hanger that supports the film. These systems may be motorized or hand-operated.

A rack-and-pinion drive and lightweight pipe or a chain and sprocket are used to move the blanket. A single-gear motor can power a large system. Although this drive is initially more expensive, it is cost-effective in reducing maintenance time. An alternate drive system consists of a gear-reduction motor that drives a shaft with cable wrapped about it. A slip clutch or a sensitive electrical overload system protects the drive. The cable slowly moves the blanket about 15–20 feet per minute. Regular maintenance is required due to cable stretching. Drive systems that anchor to sidewalls or endwalls may pull in the walls, unless they are supported to hold the cable tension.

Blanket systems must provide a tight seal all the way around. Failure to provide this will result in a chimney effect that funnels the heat from below the blanket to the attic area. If the seal isn't tight, the nighttime temperature above the blanket may be warmer than below. The type

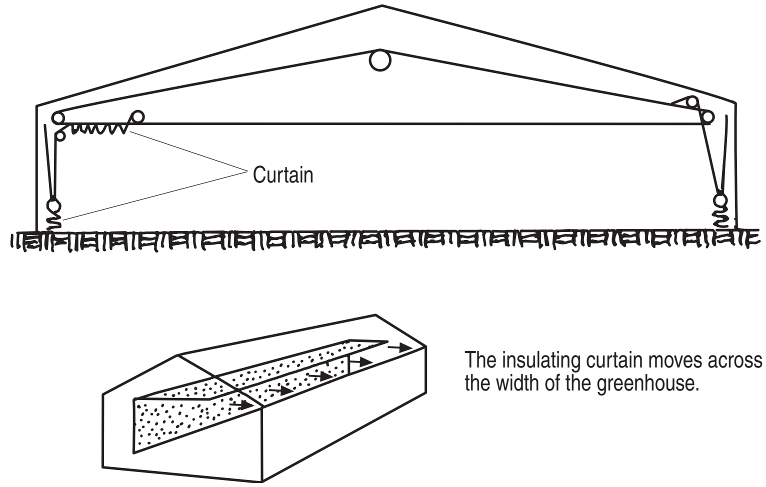


FIGURE 4-7. Blanket system for clear-span greenhouses

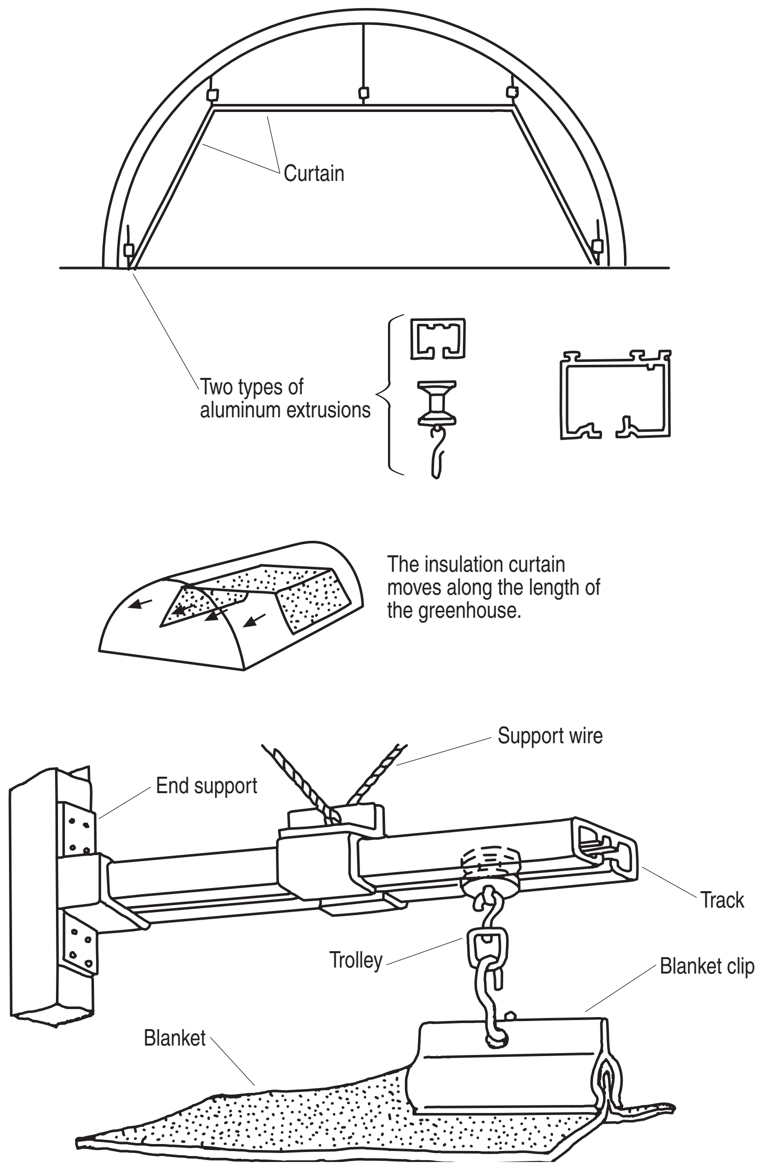


FIGURE 4-8. Aluminum track system for curved-roof greenhouses

of seal will depend on the type of installation (figure 4-9).

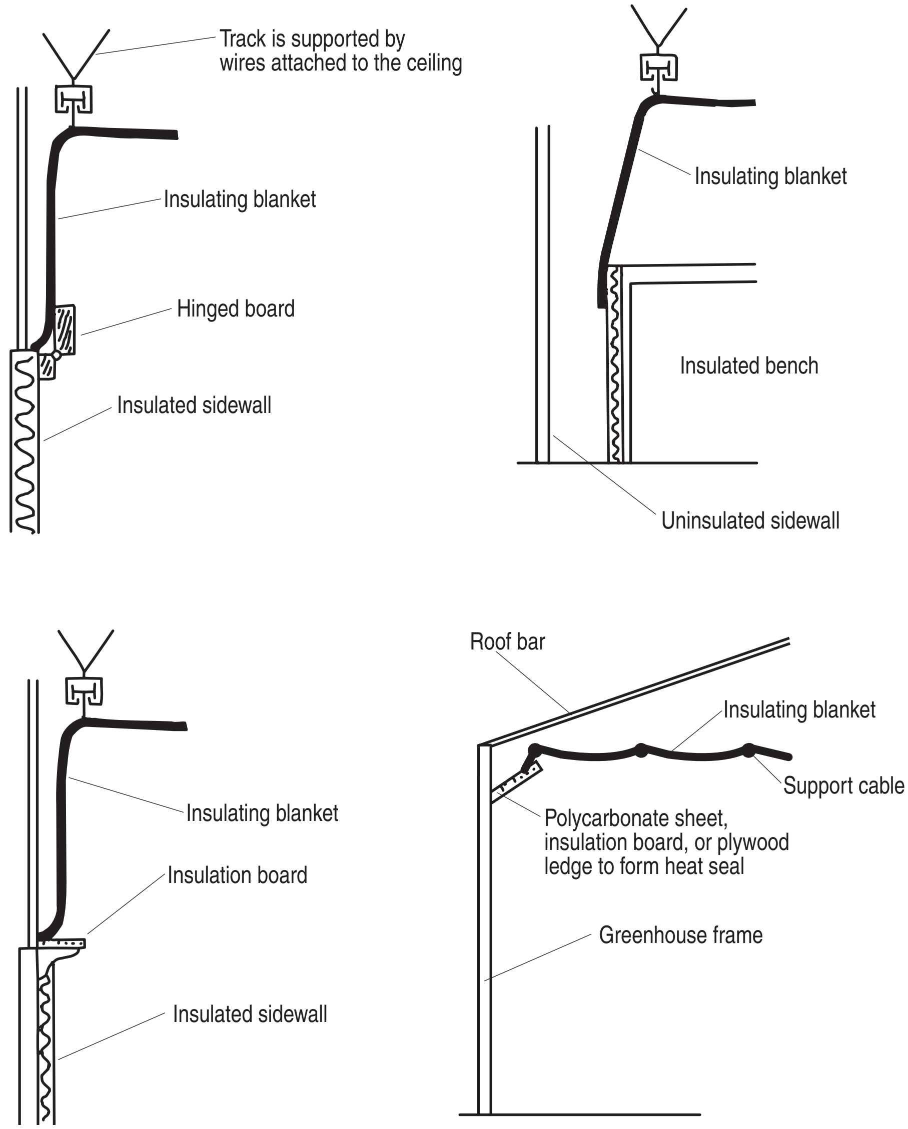


FIGURE 4-9. Blanket must seal tightly around all edges to insulate effectively

Blanket Materials

Thermal blankets are made from many different materials and may be one or more layers thick. Important characteristics of blanket materials include: heat transfer qualities, ease of handling, ability to fold for storage, durability, porosity, physical strength, cost, UV resistance, and reflective characteristics.

Porous blankets normally handle well and allow condensation or rain leakage to drain, but they are not as effective as nonporous materials in reducing energy use. Aluminizing a surface without reducing its porosity will increase its insulation value by decreasing radiation losses. These blankets are usually woven and, when made of white materials, are used for shading. A 55% woven white polyester film is a typical shade.

Nonporous materials are impervious to water and air movement. If sealed well along the edges, they save more energy than porous blankets, regardless of the material. Nonporous materials installed horizontally will collect water from roof leaks and condensation drip, which will eventually become heavy enough to cause the blanket track system to bind and fail. Although aluminized nonporous materials provide the greatest energy savings, they normally cannot be used for summer shading and require installation that prevents water accumulation.

Aluminized blankets save approximately 10% more energy than similar nonaluminized blankets. In greenhouses where the blanket temperature will be close to the interior heated air temperature, the reflective surface should face outwards to decrease radiation loss. Research comparing reflective blankets facing both directions was conducted in a large greenhouse with parallel bays. The results showed that the outward-facing reflective surface retained heat slightly better than the inward-facing surface. When artificial lighting is used under thermal blankets, the reflective side should face down to increase light reflection. Table 4-1 (page 20) lists the heat-transfer values of blanketing materials, and figure 4-10 (page 20) shows the change of the heat-transfer value with porosity and reflectivity.

MULTILAYER THERMAL BLANKET SYSTEMS

Some growers, especially those with gutter-connected, open-roof greenhouses, have installed two separate systems. One blanket is a porous material for summer shading and the other a nonporous material for winter energy conservation. In the winter, both blankets are drawn; in the summer, only one is drawn.

TABLE 4-1. Thermal performance of selected insulating blanket materials in combination with a single-layer greenhouse glazing

Material description	Heat loss through blanket and roof U-value (Btu/hour-square foot-˚F)
Spunbonded polyester	0.45–0.77
Double-knit cloth	0.60–0.65
Black polyethylene (drilled)	0.39–0.54
Reinforced polyethylene	0.41–0.50
Prefabricated aluminized vinyl	0.33–0.48
Polypropylene shade (97%)	0.28–0.46
Foylon	0.26–0.40
Aluminum/polyester strips	0.36–0.84

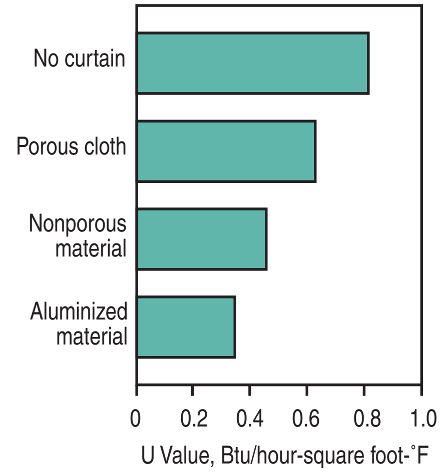


FIGURE 4-10. Heat transmission through various insulating blankets

Controls

Blankets may be opened and closed manually or automatically using a photocell or time clock. Light-actuated opening and closing is most desirable for crop production and requires no change in settings with the seasons. A light level of 50 foot-candles is a good threshold point. At this level, the blanket will remain open even on a dark, cloudy day. The time clock is the most common method of control, even though the grower must change the clock setting as the seasons change. Most environment-control computers can be programmed to operate a blanket system.

If a blanket is opened rapidly, the cold air from the attic area will flow rapidly onto the plants. Some plants are susceptible to damage from this cold air. A percentage timer that opens the blanket slowly over half an hour eliminates this problem. Some growers solve the problem by waiting for the sun to warm the attic air before opening the blankets or by partially opening the blanket 6 inches for an hour before opening the blanket entirely.

In gutter-connected ranges with large-pane, curved glass, opening the blanket too rapidly will allow the heat to rise, which warms the air too quickly and thus causes stress. This in turn can cause the glass to fracture, especially on mornings when the outside temperature is very cold.

In most snowy areas, blankets are not closed during snow storms to reduce the possibility of structural damage from accumulated snow. Where the maintenance of the greenhouse structure depends upon melting the snow with the heating system, a snow alarm should be installed to automatically open the blanket. Always provide a manual control option for all systems in the event of a power or motor failure.

Thermal Blanket Shading and Cooling

The blanket system's cost-effectiveness increases if another use can be found for it. Many growers select a system based upon summer shading and choose a white porous material that offers about 50% shade rather than a material that offers the maximum energy-saving potential. Summer shading reduces the radiant energy load on the crop, reduces leaf temperatures, reduces the time fans must operate, and makes the atmosphere more comfortable for people working in the greenhouse. However, a blanket may inhibit adequate summer ventilation in houses with ridge vents or opening roofs.

Photoperiod Control

Black blankets that block light on all edges and corners are needed for photoperiod control of some crops. The same blanket can be used for energy conservation if condensation can be drained away. The drive and support systems for photoperiod-control blankets are identical to those for thermal blankets.

Costs and Potential Savings

The most expensive parts of a thermal blanket system are the mechanical system, blanket sewing and grommet insertion, and labor costs for installation. The blanket material is probably the least expensive part.

Blanket materials vary in cost, depending upon their life expectancies and methods of fabrication. Costs generally range from $0.10 to $0.35 per square foot. The cost of installation varies with the size of the unit and the type of material selected. For large areas (20,000 square feet or more), costs are approximately $1.00 per square foot installed. For smaller houses, installation and material costs may be as high as $3.00 per square foot. The grower may install the system, but on new construction, it is generally better to have the greenhouse manufacturer or erector do the installation.

Potential savings depend upon the glazing, climate, crops grown, and overall condition of the greenhouse. Porous blanket systems offer savings of about 20%. Aluminized materials have produced savings of up to 70% when closed. The annual savings will be slightly less, depending upon the percentage of energy used during the daytime. In an area of 5,000 degree days, the yearly heating energy cost in a single-glazed greenhouse is about $1.20 per square foot for a night thermostat setting of 60˚F using heating oil at $1.20 per gallon. A good blanket system can reduce energy costs by $0.40 per square foot per year. This savings will pay for the installation in two to three years. Smaller houses or those with less efficient blankets will require more time to pay back the investment. In all cases of new construction, considering both benefits of reduced winter heating costs and summer shading and cooling, movable blanket systems are a sound economic choice.

Factors to Consider Before Installation

- Retrofitting older greenhouses can be difficult. However, in most ranges, a system that moves post-to-post or truss-to-truss can be installed with little interior alteration. Heating system pipes and heaters should be moved to below the blanket.

- Condensation that accumulates on top of a blanket can quickly destroy the system. Porous aluminized materials drain effectively.

- Seal the ends and edges of blankets tightly, so that minimum air exchange occurs between the growing area and the attic (see figure 4-9, page 19).

- Humidity levels will be higher in a greenhouse with a blanket. Evening temperatures will not fall as rapidly as in a house with no blanket. Management may need to change scheduling to accommodate these modifications.

- In heavy snow areas, design the heating system large enough to heat the greenhouse when the blanket is open during snow storms.

- A retracted blanket partially shades the greenhouse, in some cases by as much as 10%. Consider storage along the north wall or under a gutter to reduce shading.

- Plan a technique for opening the blanket in the morning to reduce the effect of cold air settling from the attic. Since the system is mechanical, inspect and maintain it regularly. Most growers open the blanket a few inches first to allow some of the cold air to settle down and the heated air to rise above the curtain.

- Anticipate and remove obstructions that may tear the blanket. Hanging plants may interfere with the blanket. Allow for shrinkage of the blanket materials and dirt or dust accumulation, particularly on white shade cloth.

5 Fuels and Heating

Common Fuels

Gaseous Fuels

Natural gas is one of the most economical fuels, although it is not available in all areas. It needs no on-site storage, and supplying it to the burner is simple. Natural gas burns cleanly, requires little equipment maintenance, and may be used in central boilers or remote unit heaters. Some supply companies include an "interruptible clause," which allows them to interrupt service in time of extreme need, usually during cold spells when fuel is needed to heat homes. A backup heating system is essential in these areas.

Propane is a clean, gaseous fuel much like natural gas. Although more expensive than natural gas, it can readily be obtained where natural gas is not available. Maintenance is minimal, but storage tanks and preheaters are needed.

Fuel Oil

No. 2 oil is usually comparably priced with natural gas but may be more expensive in some locations. A relatively clean fuel that demands slightly more burner maintenance than gas, oil requires on-site storage tanks. Most installations are above ground and require a containment systems in the event of a spill. Oil stored in above-ground tanks becomes difficult to pump in temperatures near 0°F. Insulated tanks or additives in the fuel protect against this hazard.

No. 4 and 6 oils have a higher heating value than no. 2, but, because of low sulfur restrictions, they are similar in price per Btu to no. 2 oil. These oils require preheating and continued attention to equipment. They are subject to the same storage and temperature limitations as no. 2 oil.

Solid Fuels

Wood and coal are important heat sources for greenhouses in some areas. Growers who have installed these systems have generally been pleased with the results. Average payback periods are usually one to three years. The supply of fuel has been adequate, and the security of having fuel on hand before the heating season, at a known price, helps in planning production. Additional labor and maintenance are required with these systems.

Coal is a low-cost fuel source in some areas. One ton of coal has the equivalent heating value of 150–180 gallons of fuel oil. Although the potential savings that may be attained by converting to coal seem significant, consider some additional factors. More labor is required to burn coal than to burn oil, even if an automatic stoker is used. Most large systems require a night operator to oversee the heating plant. Coal produces large quantities of ash, which must be removed and disposed of in an acceptable manner. Low-grade soft coal requires expensive stack pollution control equipment. In some areas, it is difficult to receive permission to burn coal.

Covered storage bins are often built where freezing occurs. The storage hopper bottom unloader must be properly designed to keep the coal from bridging over and not flowing. Coal should be covered to prevent pollution of nearby water sources.

Operating a coal-fired unit is much more difficult than setting the thermostat on an oil furnace or boiler. Coal, with an ignition temperature of 800°–900°F, is more difficult than wood to start and to keep burning.

Wood and wood wastes are a widely available renewable resource in most colder parts of the United States.

Wastes are available in several forms:

- sawdust from sawmills and wood-product manufacturing plants
- wood chips from land clearing and right-of-way maintenance
- cordwood from logging operations and from harvesting poor-quality trees
- pellets or wafers as a uniform product for use with automatic stokers

Wood wastes are sold by the ton or cord. A ton of dry sawdust as received from a furniture manufacturer will have the heat equivalent of 100 gallons of fuel oil. If the sawdust or chips are green as they come from a sawmill or chipping operation, the heat value is about 50 gallons of fuel per ton. A cord of air-dried hardwood, cut at least twelve months before use, is equivalent to 240 gallons; if fresh cut, about 150 gallons. These are heat values before furnace efficiency is considered. The price varies widely and is affected by heat value, distance hauled, availability, and the fuel's value for other uses. A covered storage area is desirable. Tables 5-1 and 5-2 show approximate heat values of wood fuels.

TABLE 5-1. Weight and approximate heat value of common fuel woods

Species	Weight per cord: Green (pounds)	Weight per cord: Air-dried (pounds)	Approximate heat value,[a] 60% efficiency furnace (Btu's)
Ash	3,840	3,440	16,500,000
Aspen	3,440	2,160	10,400,000
Beach	4,320	3,760	17,300,000
Yellow Birch	4,560	3,680	17,000,000
American Elm	4,320	2,960	14,300,000
Shagbark Hickory	5,040	4,240	20,400,000
Red Maple	4,000	3,200	14,000,000
Sugar Maple	4,480	3,680	17,400,000
Red Oak	5,120	3,680	16,900,000
White Oak	5,040	3,920	18,300,000
White Pine	2,880	2,080	9,500,000

[a] Based on a standard 4-foot-by-4-foot-by-8-foot cord

TABLE 5-2. Weight and heat value of alternate forms of wood

Type	Weight (pounds/cubic foot)	Volume (cubic feet/ton)	Heat value (Btu/ton)
Sawdust			
green	10–13	150–200	8–10,000,000
kiln-dried	8–10	200–250	14–18,000,000
Chips	10–30	67–200	16–20,000,000
Hogged	10–30	67–200	16–20,000,000
Pellets	40–50	40–50	18–20,000,000
Bark	10–20	100–200	16–18,000,000
Rubber pellets	50–55	35–40	32–34,000,000

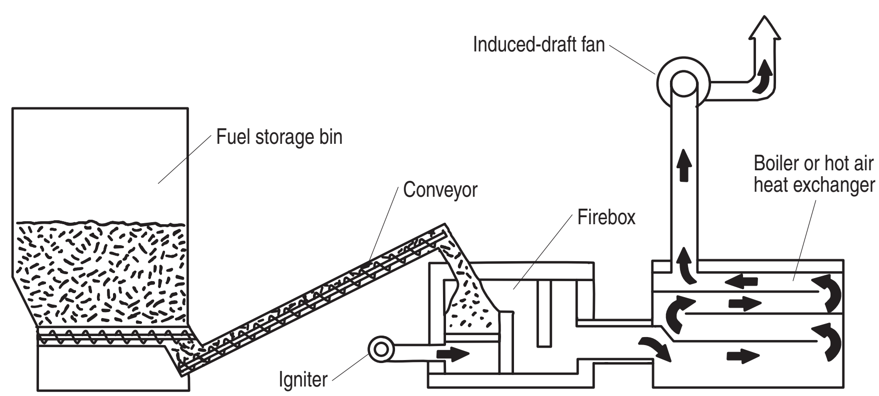


FIGURE 5-1. Wood chip furnace schematic

Solid Fuel Equipment

Wood and coal require a substantial capital investment in new furnaces or boilers, fuel-handling equipment, storage buildings, and pollution-control devices. Small furnaces and boilers with a 100,000–300,000-Btu/hour output are available for $1,000–$2,000 through stove shops and heating contractors. Larger units are generally available directly from the manufacturer (figure 5-1). Costs for these units are difficult to estimate because of the wide variety of equipment options and the diversity of individual installations. Small radiant wood or coal stoves are not recommended, because they produce uneven heat output and require frequent stoking and cleaning.

Before any decision is made, apply for a permit from the state environmental regulatory agency. Emissions of particulate matter and smoke must be kept below specific levels, which may require special pollution-control and monitoring equipment. In addition, operators may need to be licensed.

Operation and maintenance costs are considerably greater for a wood- or coal-fired system than for comparable oil-fired units. Handling and ash removal require extra personnel time, and larger units may require a night operator. Ash disposal may be a problem in some areas, as it may be considered a toxic waste.

Electric Heat

Electrical heating systems operate at 100% efficiency but also at the highest cost. Installation is relatively easy if existing service entrance wiring capabilities are not exceeded. This type of heating is sometimes used in a propagation area, office, or work area for spot heating.

Energy Conversion Efficiencies

When fuel is converted to heat by combustion, energy loss generally takes place in three ways: (1) incomplete combustion, (2) poor heat exchanger performance, or (3) loss in the heat distribution system.

Incomplete combustion occurs when not all of the fuel is converted to hot gases, causing accumulation of soot, formation of toxic gases, and possibly warping or cracking of the heat exchanger. Complete combustion in gas- or oil-fired units depends upon nozzle design and a proper air-to-fuel ratio. Loss occurs when nozzles are worn or improperly adjusted. Table 5-3 shows fuel loss resulting from accumulation of soot in the firetubes.

Poor heat exchanger performance can be caused by dirty surfaces, soot in the firetube, water scale on boiler tubes, and so on. Some losses are necessary to vent harmful combustion gases up the exhaust stack. Reducing the temperature of the exiting air can cause condensation on the heat exchanger. This moisture can react with sulfur dioxide in the exhaust gases to form sulfuric acid and cause premature heat exchanger failure.

Loss in the heat distribution system occurs when hot water or steam is transported over long distances or when surfaces in mechanical rooms or the headhouse are uninsulated.

Table 5-4 shows conversion efficiencies under optimum and typical operating conditions (dirty flues, faulty steam traps, etc.). Regular maintenance keeps equipment operating closer to the optimum range.

Fuel Cost Comparisons

Because different fuels supply varying quantities of heat per unit of measure (gallons, cubic feet, ton) and heat conversion efficiencies vary, cost comparisons among fuels can be difficult. Table 5-5 compares the costs of various fuels on the basis of their heating equivalents as expressed in dollars per million Btu's ($/MBtu). To use the table, draw a vertical line through the price of the fuel being considered to the Heating Equivalent Cost line. This line shows the price per MBtu. For example, fuel oil at $1.20 per gallon has an equivalent fuel cost of $11.75 per MBtu and is equivalent to natural gas at $0.82 per therm or green wood chips at $67.00 per ton.

The choice of fuel for greenhouse heating should depend on more than

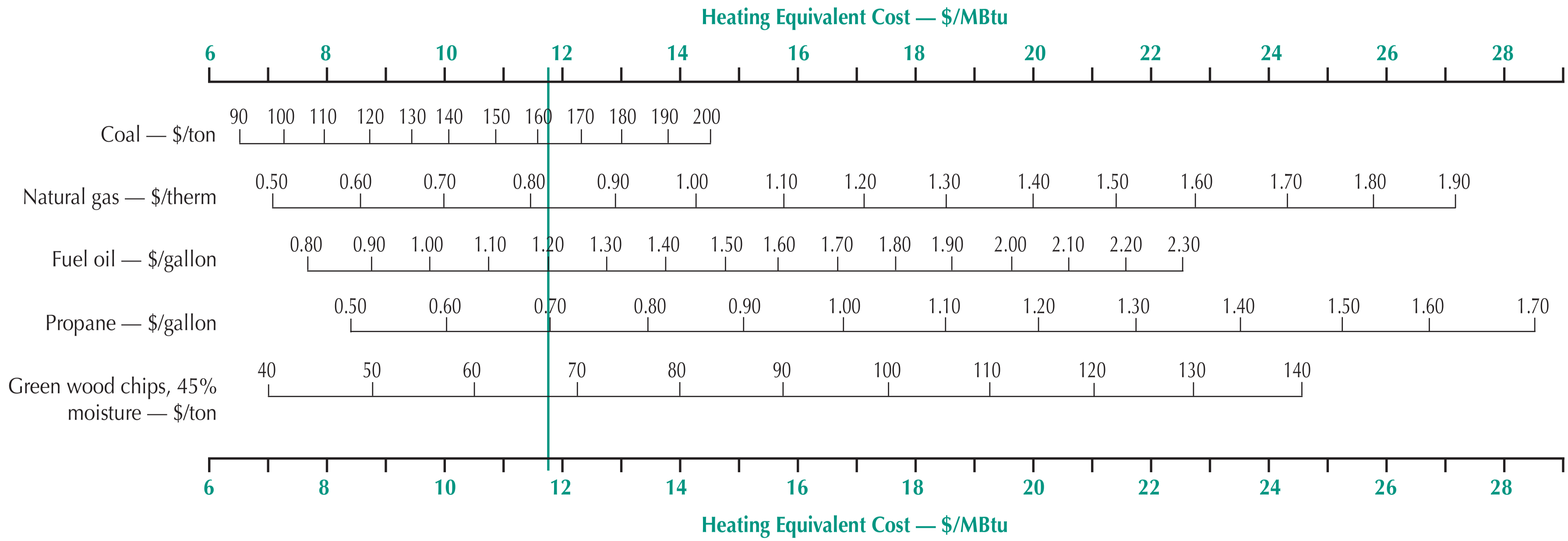
TABLE 5-3. Effect of soot on firetube heat transfer

Thickness of soot in firetubes (inches)	Loss of efficiency in firetubes (%)	Average fuel loss (%)
1/32	9.5	2.9
1/16	26.2	7.8
3/32	35.7	10.7
1/8	45.3	13.6
3/16	69.0	20.7

TABLE 5-4. Heat values and conversion efficiencies for different energy sources

	Efficiency (%)		
Fuel	Optimum	Typical	Heat value
Anthracite coal (hard)	70	60	13,000 Btu/pound
Bituminous coal (soft)	70	60	12,000 Btu/pound
Natural gas	85	70	1,000 Btu/cubic foot (100,000 Btu/therm)
Propane	85	70	85,000 Btu/gallon
No. 2 fuel oil	85	70	140,000 Btu/gallon
No. 6 fuel oil	85	70	150,000 Btu/gallon
Dry sawdust, 13% moisture	85	60	7,800 Btu/pound
Wood chips, 45% moisture	75	50	3,800 Btu/pound

TABLE 5-5. Fuel cost comparison



Assumptions:

COAL — 13,000 Btu/pound; 60% efficiency; $/MBtu = $/ton ÷ 13.8

NATURAL GAS — Therm = 100,000 Btu; 70% efficiency; $/MBtu = $/therm x 14.3

FUEL OIL (Average #2 and #6) — 145,000 Btu/gallon; 70% efficiency; $/MBtu = $/gallon x 9.8

PROPANE — 85,000 Btu/gallon; 70% efficiency; $/MBtu = $/gallon x 16.8

WOOD CHIPS (45% moisture) — 3,800 Btu/pound; 75% efficiency; $/MBtu = $/ton ÷ 5.7

Note:

This table compares the costs of various fuels on the basis of their heating equivalents expressed in dollars per million Btu's ($/MBtu). To use the table, extend a vertical line from the price of the fuel being considered through the "Heating Equivalent Cost" lines above and below. This line shows the price per MBtu.

For example, fuel oil at $1.20 per gallon has an equivalent fuel cost of $11.75/MBtu and is equivalent to natural gas at $0.82 per therm or green wood chips at $67.00 per ton. (This example is shown by the green vertical line on the table above.)

cost alone. Fuel availability is another important consideration. Many growers install combustion units that can burn more than one type of fuel. If dual fuel capability is not possible, another system may be added to handle an alternative fuel.

Computer programs have been developed by commercial organizations and some cooperative extension services to help growers determine yearly and monthly operating costs based on the type of greenhouse, type of energy-saving blanket, outside design temperature, nighttime set point temperature, and cost of fuel.

Heating Systems

Both central or unit space heaters are available for greenhouses (figures 5-2 and 5-3). The choice of system depends on the type of fuel available, initial cost of the system, grower preference, and amount of greenhouse space to be heated. A central heating system operating at peak efficiency is usually preferable to many small unit heaters placed throughout the greenhouse. Greenhouse ranges of more than one-half acre usually have a central heating system.

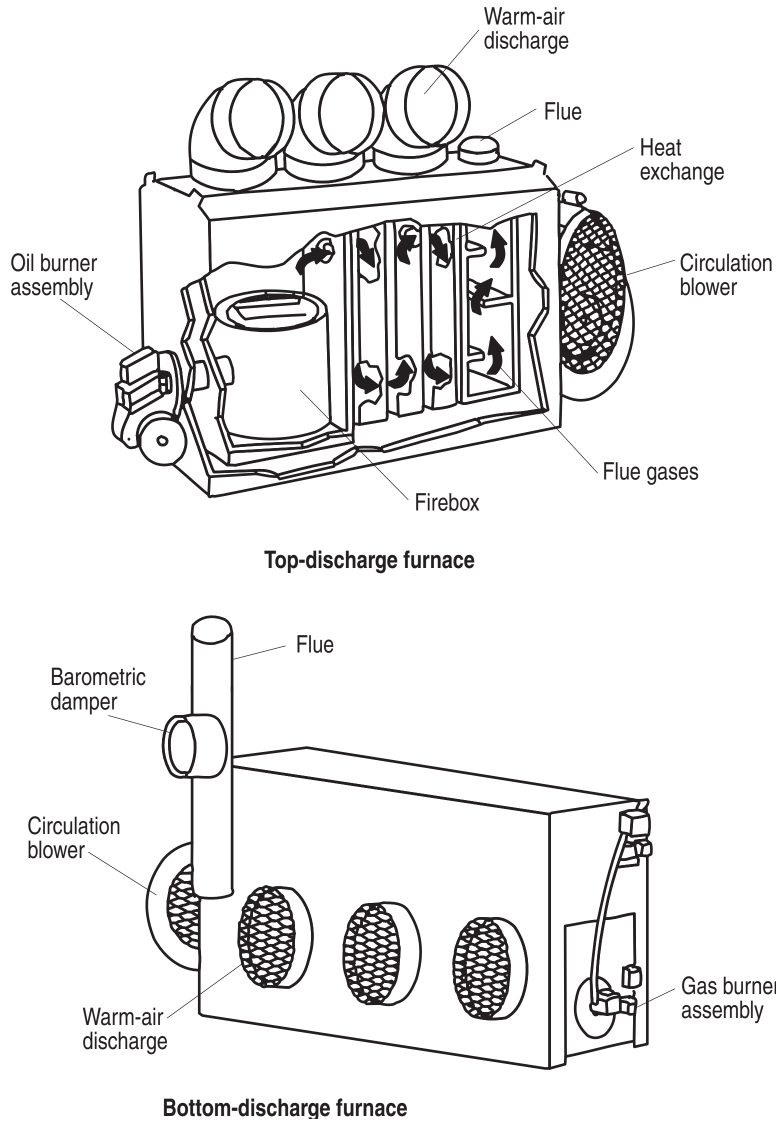


FIGURE 5-2. Direct-fired, floor-mounted, warm-air furnaces

Some growers have saved considerable fuel by replacing an old inefficient central boiler with several hot-air unit furnaces. This eliminates the significant heat losses in the poorly insulated distribution system. The hot-air system is more efficient and can be easily shut off if a portion of the range is not in use.

Central heating systems, either hot water or steam, require one or more boilers, valves, pumps, and other necessary controls. Heat is transferred to the greenhouse either by smooth or finned pipes or by unit heat exchangers with fans. Most piping is placed on the perimeter, with the remainder placed overhead and beneath gutters or benches. Central systems also make it easier to convert from one fuel source to another, a significant consideration with the uncertainty of fuel availability or cost.

Hot water central heating systems are generally simpler to install, less complicated, and less maintenance-intensive than a steam system. Hot water system pipes heat more slowly, but temperatures are normally more uniform. Modulating or mixing valves provide accurate temperature control with some energy savings, because they lower the temperature of the water pumped through the heating pipe as the temperature of the greenhouse nears the set point. When the control system stops the pump, the pipe is filled with water close to the temperature of the greenhouse. When mixing valves are not used, the water temperature in the pipe is near 180°F. This excess heat in the pipe system causes the temperature to overrun the set point, which uses more energy than necessary. This can be an even greater problem with steam.

Zoning is easier with a boiler system, as circulating pumps are used to move the heated water in the pipes, and each pump can be controlled by a separate thermostat. If properly designed, zoning can provide a different temperature in each section of the greenhouse.

Steam systems rapidly heat the lines, and because of the higher temperatures usually need less pipe. A steam system requires a high initial investment, but it has a long life expectancy. Steam systems are not normally installed in greenhouses because of the difficulty in getting good temperature control and the lack of installation and service people who understand their operation.

Unit space heaters, either mounted overhead or on the floor, are popular for individual hoophouses or small gutter-connected ranges. Unit heaters require a moderate capital investment, are easy to install, and allow easy expansion of facilities. However, the life of a unit heater in the high-humidity greenhouse environment is short. Because the heaters are typically fueled by oil or natural gas, combustion air must be vented into the greenhouse and combustion byproducts vented out. Unless there is a damper on the chimney, warm air is always being drawn out of the greenhouse, whether the unit is burning or not. Leaking fuel lines, lack of adequate combustion air, or unvented or improperly vented heaters may result in fumes harmful to plants and workers. Always vent unit heaters to the outside. Mount the exhaust stack at least 2 feet above the highest ridge of the house (figure 5-4).

An adequate primary air supply is necessary for complete combustion. Provide 1 square inch of makeup air opening for every 2,000 Btu/hour output of the furnace or boiler. An inlet pipe is often run through the outside wall directly to the heater. It should be capped and located so that the intake is above the highest snow level.

Traditional gravity-vented units have been largely replaced by power-exhausted units or separate combustion furnaces that increase efficiency by about 20%. The power-exhaust unit uses a blower to create a positive flow

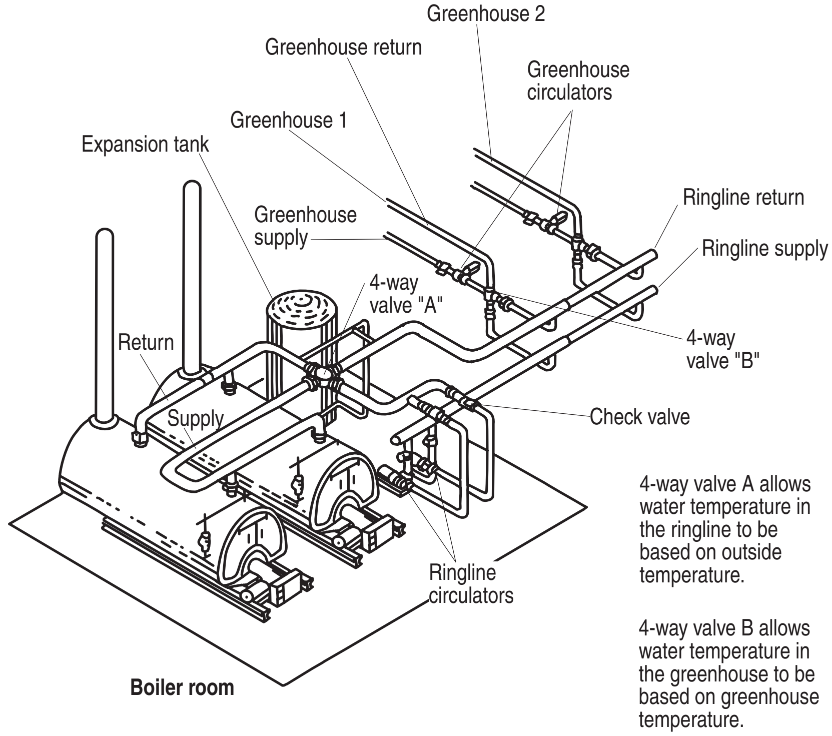
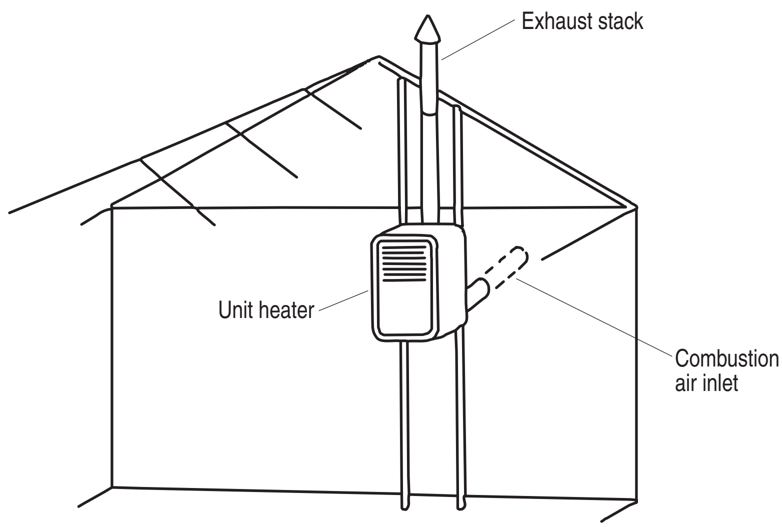


FIGURE 5-3. Central boiler system with ringline and four-way mixing valve



Provide 1 square inch of opening for combustion air for each 2,000 Btu/hour output. Always vent unit heaters to the outside. Mount the exhaust stack at least 2 feet above the highest ridge of the house.

FIGURE 5-4. Unit heaters

of exhaust gases through the heat exchanger and exhaust pipe. In separate combustion units, drier outside air is brought in for combustion.

Heat Distribution

A well-designed heating system distributes heat evenly to encourage uniform and predictable crop growth.

With a furnace or unit heater, the simplest and most effective system is using horizontal air flow (HAF) circulation fans to maintain uniform temperature, humidity, and carbon dioxide levels at leaf surfaces. The system utilizes 16- to 20-inch-diameter, $^1/_{15}$-horsepower fans to move the air down one side of the greenhouse and back up the other side (figure 5-5). The fans are located one-quarter of the width in from the sidewall on a single-span greenhouse and in the center of each bay in a gutter-connected house. They can be placed 7–10 feet above the floor so they are out of the way. The fans, which operate continuously, mix the air and provide a uniform temperature throughout the greenhouse. Heat from one or more furnaces or unit heaters can be added to the air stream anywhere.

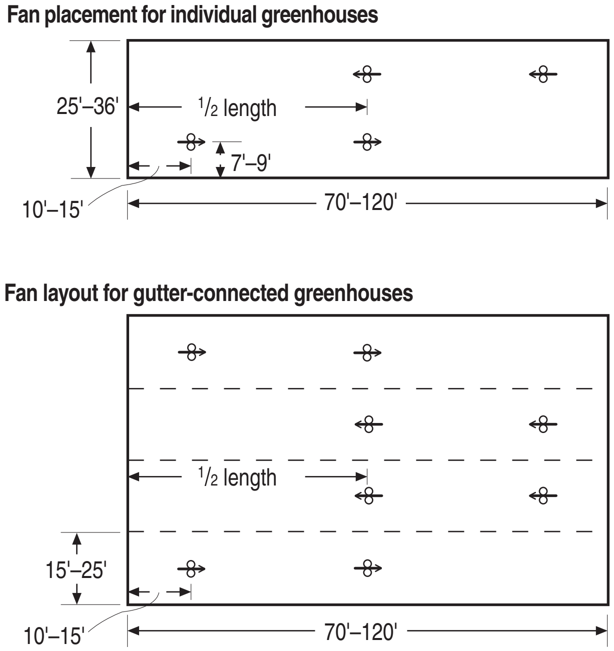


FIGURE 5-5. Typical fan arrangements in a greenhouse with horizontal air circulation (HAF)

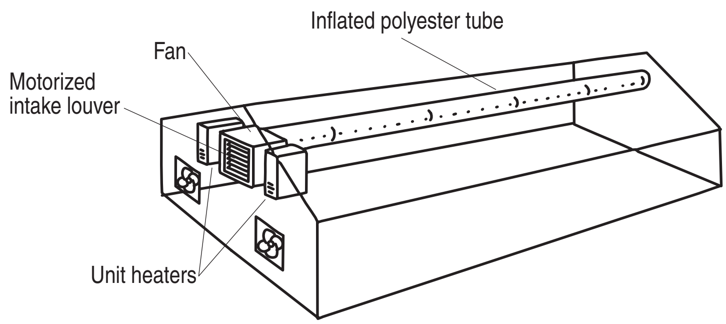


FIGURE 5-6. Heat distribution via overhead perforated plastic tubes

Another common system uses perforated poly tubes located in the ridge or under the benches (figure 5-6). Heat from the furnace is added before the fan or blower that inflates the tubes.

Heat from a boiler system can be distributed in several ways. Piped hot water systems may use bare or finned pipes (figure 5-7). Finned piping provides greater heat transfer per unit length because of the increased surface area exposed. For example, a $1^1/_4$-inch bare steel pipe with 180°F water delivers about 117 Btu/hour-foot of pipe. A $1^1/_4$-inch steel pipe with thirty-eight $4^1/_4$-inch-by-$4^1/_4$-inch fins under the same conditions delivers about 1,200 Btu/hour-foot—over ten times more heat transfer.

High-output finned pipe works best overhead, under gutters, or on exterior walls. It should not be placed under benches; because of its high output, it unevenly dries the soil in the bench or in the containers on the bench. Low-output fin or bare pipe can be placed under benches, and the water temperature may be lowered if necessary to prevent differential soil heating and drying (figure 5-7). Bare pipe is often preferred on long runs, because its lower heat transfer rate maintains more uniform temperatures along the length of the greenhouse. The use of mixing valves on hot water systems can ensure uniform continuous convection by maintaining warm water in the heat distribution system at all times.

Floor heating is desirable for crops grown directly on the floor. Designs usually call for polyethylene pipe, polyvinyl chloride pipe, or EPDM (ethylene propylene diene monomer)

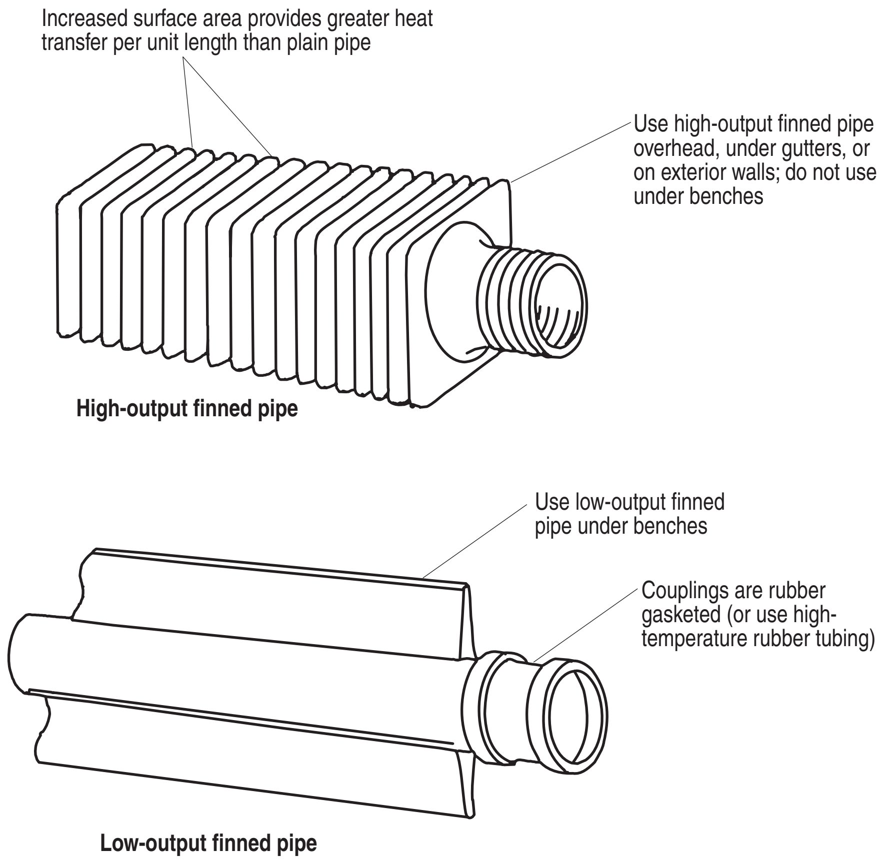


FIGURE 5-7. Finned heat pipe

rubber tubing embedded 2–16 inches on-center in concrete, gravel, or sand. This system significantly reduces energy costs, since the air temperature within this type of greenhouse is lower than in conventionally heated houses. Crops that require little hand work during their growth period, such as spring bedding plants and fall poinsettias, are excellent choices for this system. Floor heat is also being installed in flooded-floor installations. A typical temperature pattern for a poinsettia crop in November would be a floor temperature of 74°F, a soil temperature of 64°F, a canopy temperature of 59°F, and a temperature of 55°F at the 6-foot level. This temperature pattern is reversed from what is normally found in houses with overhead heating, where the floor temperatures are 5°–10°F cooler than at the 6-foot level. Figure 5-8 (page 30) shows a typical floor heating system.

Bench heating systems operate in the same way as floor heating, but air temperature cannot be reduced as much. Figure 5-9 (page 30) shows a typical installation of EPDM tubing in a twinwall configuration. The double-tube configuration creates an even temperature throughout the entire loop. If the temperature is 105°F in the intake manifold and 95°F in the return manifold, the average temperature at the halfway point in the loop is 100°F. Since the return runs conterflow to the supply, the average at any point in the system is also 100°F.

Floor and bench heating systems maintain uniform temperatures by transferring heat over large surface areas. Both systems have positive effects on the microclimate of the plants. Gentle air movement caused by the warmer floor or bench eliminates stagnant air pockets and lowers the humidity around the plants. Generally, these systems reduce the time required to grow a plant to maturity.

Floor and bench heating cannot supply the entire heating demand during the coldest months and require supplementation by either a hot-water or hot-air system. A few low-cost, widely spaced unit heaters can provide the additional heat required. The floor system seems to even out the temperature throughout the greenhouse, so the temperature differences normally associated with unit heaters are not present.

A greenhouse with bedding plants on a porous concrete floor, with 105°F water flowing through embedded polybutylene pipe on 12-inch centers, heats at the rate of 20 Btu/square foot/hour when the ambient air temperature is 55°F. This rate varies with the crop grown, the temperature of the water, and greenhouse ambient conditions. This energy will provide between 30% and 60% of the total design load for most locations.

Pipe Insulation

Bare or poorly insulated heating system pipes waste a considerable amount of heat each year in areas such as boiler rooms or headhouses, where heat is not needed or where it should be controlled. This heat loss continues every day the system is operating.

The payback for insulating pipes usually takes less than two years. Installation is simple and can be done by unskilled workers.

Heat loss from pipes depends on several factors, including the size and

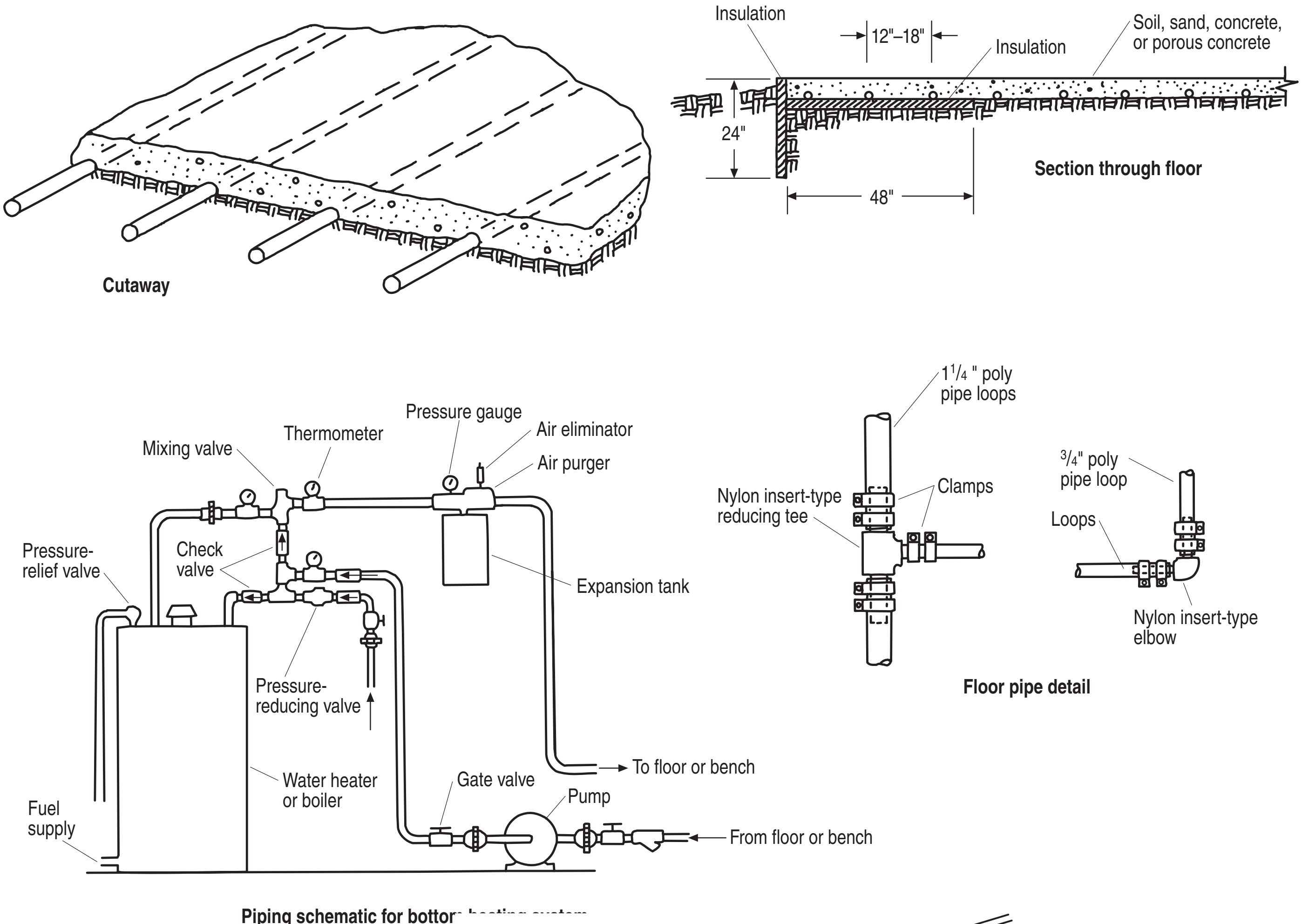


FIGURE 5-8. Floor heating system

length of the pipe, the temperature of the water or steam, the air temperature surrounding the pipe, and the length of time the pipe is hot. Adding insulation slows this loss, reduces the time the heating system has to operate, and therefore reduces fuel bills.

Table 5-6 gives an approximate annual savings from insulating a linear foot of different-diameter pipes with 1-inch-thick fiberglass or foam insulation. It assumes 2,000 hours of annual heat (typical of heating system operation in a northern climate), fuel oil at $1.20 per gallon, and a 70°F room temperature. Values in the table should be reduced about 10% for $^3/_4$-inch-thick insulation and

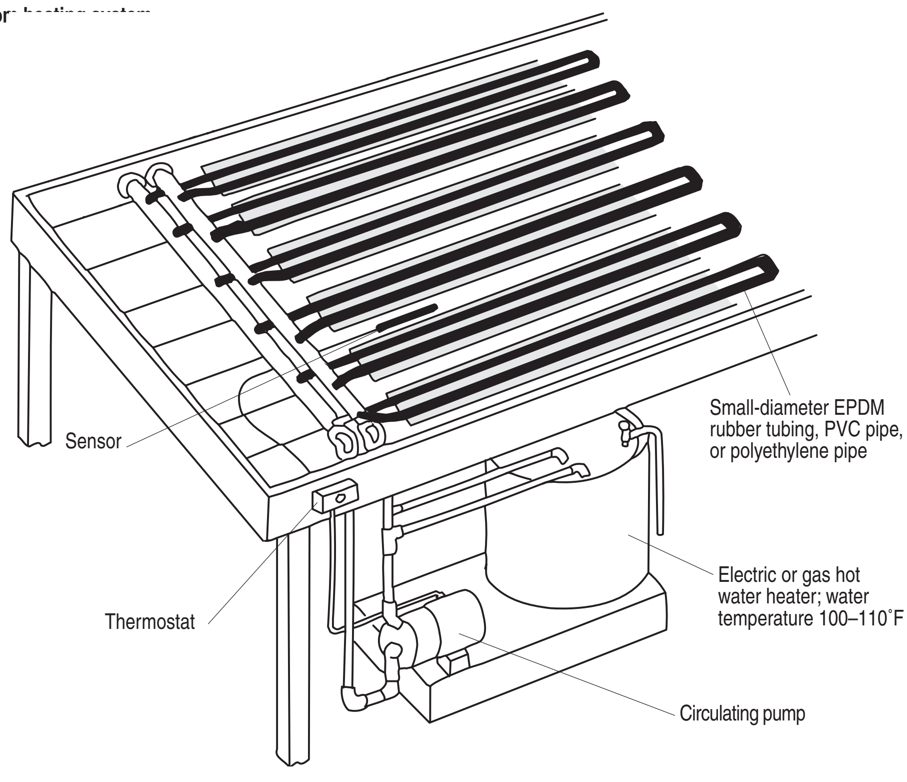


FIGURE 5-9. Typical warm-water root-zone heating system with tubing, a circulating pump, a source of hot water, and a control system

20% for $^1/_2$-inch-thick insulation. Because of the higher cost, values should be decreased about 50% if LP gas is used as a fuel.

Insulation Materials

Flexible or semirigid foam insulation is available at most home building centers for $^1/_2$- to 1-inch pipe. It comes in lengths of 3 or 6 feet and is easy to apply by slipping it over the pipe and taping the joints. Its limiting factor is a maximum allowable 220˚F temperature, which makes it undesirable for steam systems.

Fiberglass with a factory-applied jacket is a better choice for larger pipes and temperatures over 200˚F. Special preformed pieces are available to fit over valves and fittings. This material can be purchased from heating supply contractors. Insulation in areas where damage from carts or rolling benches may occur should be pro tected with a rigid sleeve.

Pipes that run underground or outdoors between buildings should have a waterproof covering such as an aluminum jacket. This keeps the insulation dry, retaining its insulation value.

Table 5-7 can be used to estimate the cost of insulation for different pipe sizes. Multiply the value in the table by the number of linear feet to get the cost. For example, 50 feet of 1-inch-thick fiberglass insulation for a $1^1/_2$-inch pipe will cost $75 ($1.50/linear foot x 50 feet = $75). If you have a heating contractor install the insulation, you can expect to pay about $1.50 per linear foot for labor for the small sizes and about $2.50 per linear foot for larger sizes. If you install it using your own labor during slack periods, the cost may be considerably less.

TABLE 5-6. Approximate annual savings from insulating heating/hot water pipes — per linear foot

Nominal pipe diameter (inches)	180˚F hot water	5 psi steam
$^1/_2$	$1.22	$1.36
$^3/_4$	1.50	1.72
1	1.86	2.15
$1^1/_4$	2.35	2.69
$1^1/_2$	2.70	3.06
2	3.33	3.79
3	4.80	5.50
4	6.08	6.96

Note: Above table assumes:
- 1-inch-thick fiberglass or foam insulation
- Fuel at $11.75/MBtu (fuel oil at $1.20/gallon)
- 70˚F room temperature
- 2,000 hours of annual use
- Decrease values 50% for propane heat

Values in the table should be reduced about 10% for $^3/_4$-inch-thick insulation and 20% for $^1/_2$-inch-thick insulation. Because of the higher cost, values should be decreased about 50% if LP gas is used as a fuel.

TABLE 5-7. Approximate cost of pipe insulation

	Cost of pipe insulation ($/linear foot)		
Pipe size (inches)	Foam, $^1/_2$ inch thick	Foam, $^3/_4$ inch thick	Fiberglass, 1 inch thick
$^1/_2$	$0.40	$0.65	$1.05
$^3/_4$	0.50	0.85	1.10
1	0.70	1.25	1.20
$1^1/_4$	0.80	1.65	1.40
$1^1/_2$	1.00	1.85	1.50
2	1.50	2.00	1.65
3			2.00
4			3.45

Note: Multiply the value in the table by the number of linear feet to get the cost. For example, 50 feet of 1-inch-thick fiberglass insulation for a $1^1/_2$-inch pipe will cost $75 ($1.50/linear foot x 50 feet = $75).

A simple payback can be calculated from the formula below. For savings in fuel, see table 5-6.

$$\text{Simple payback} = \frac{\text{Cost of materials and labor}}{\text{Savings in fuel}}$$

Using the above example and having the insulation installed by a heat ing contractor, the payback would be:

$$\text{Simple payback} = \frac{(50 \text{ feet x } \$1.50/\text{foot}) + (50 \text{ feet x } \$1.50/\text{foot})}{50 \text{ feet x } \$2.70/\text{linear foot}} = 1.1 \text{ years}$$

Controls

The best heating system has little value if its controls do not work properly or are incorrectly located. Temperatures below optimum levels reduce productivity and delay crop maturity, which results in market losses. Temperatures above optimum levels waste energy and also cause crop timing and quality problems. For example, when the outside air temperature is 40°F, a greenhouse maintained at 62°F will use 10% more fuel than the same house maintained at 60°F.

Mechanical Thermostats

Typical home heating thermostats have an exposed bimetallic strip sensing element that can give erroneous signals when covered with dust or moisture. The differential between the on and off setting in these thermostats is usually 3°–6°F. For example, if a heating thermostat is set at 65°F and the differential is 5°F, the furnace will start when the greenhouse temperature drops to 60°F but will not shut off until the temperature reaches 70°F. A better choice for greenhouses is one that has a sensor activated by pressure from the expansion of a liquid or gas in a coil of closed tubing.

Line-voltage thermostats are used with most unit-type furnaces and heaters. They connect the motors on the heating unit directly to the electric supply. They operate at 120 or 240 volts.

Low-voltage thermostats are commonly used with central heating systems. A transformer lowers the voltage to 24 volts, and relays are used to turn the motors on.

Two-stage thermostats have two separate sets of switches. They are used where two levels of control are desired, such as with fan ventilation. For example, the first stage set at 80°F will open the louvers and turn one fan on. If the temperature in the greenhouse continues to rise to 85°F, the second stage will activate the second fan. The differential between stages may be fixed or variable.

Shield thermostats to protect the bulbs from the sun. Draw air across them with a small fan so they quickly sense the greenhouse environment. Figure 5-10 illustrates an aspirated thermostat box and compares temperature readings between aspirated and nonaspirated thermostats. The temperature spread lowers from 8°F to 2°F during aspiration. Energy is wasted any time the greenhouse air temperature is heated above the set point.

Construct aspirated thermostat shelters with white-painted plywood, and place them so they face north and are accessible in the center of the greenhouse. Keep them away from exterior walls or from the direct influence of a unit heater or hot water pipe.

Central heating systems use more sophisticated controls, including proportional action. Proportional controls are particularly suited to hot water systems, where mixing valves modulate to control water temperature.

Remote bulb thermostats are used for controlling the circulating pumps for root zone heating. The bulb on the copper tube has a gas or liquid that contracts and activates a switch as the soil is cooled (figure 5-11). The bulb should be placed in the growing media of a representative container to give good control.

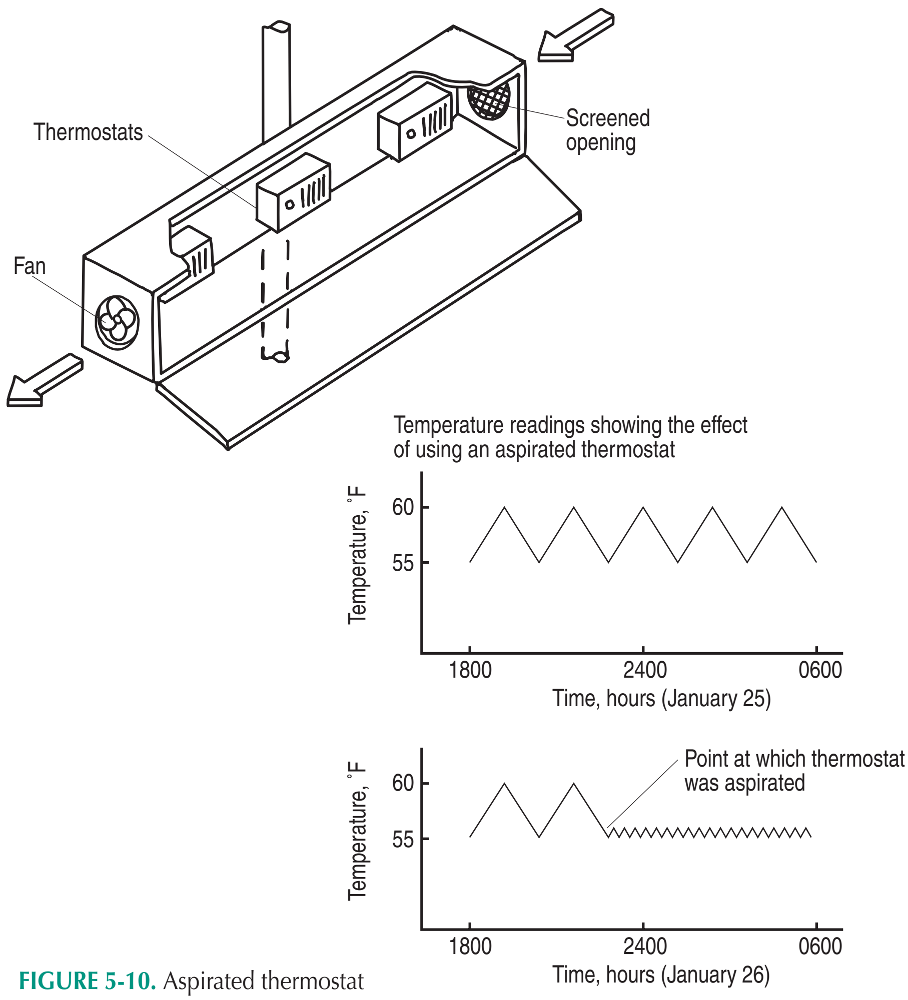


FIGURE 5-10. Aspirated thermostat

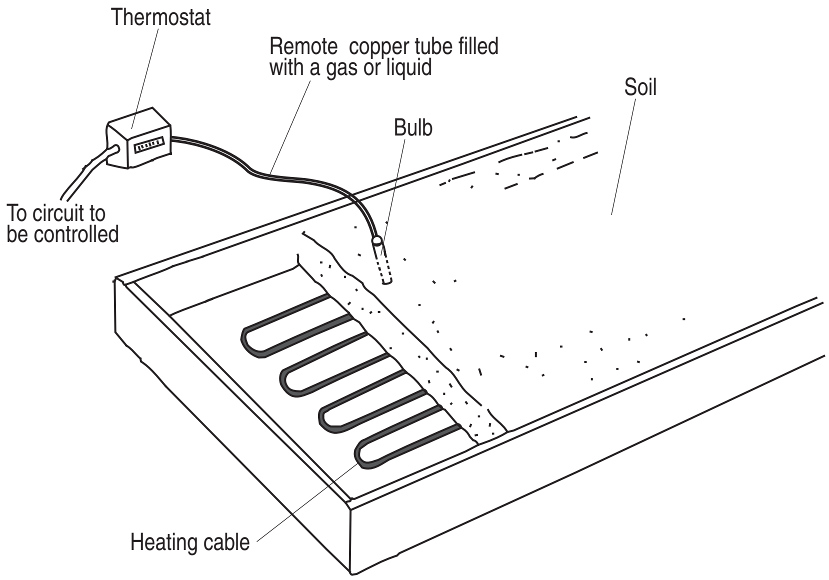


FIGURE 5-11. Remote-bulb thermostat used to control root zone heating

Electronic Thermostats

The standard mechanical thermostat used to control furnaces, boilers, and fans can be replaced by a more accurate and versatile electronic thermostat. Although they cost slightly more initially, the savings in energy will offset the cost in a short time.

The typical capillary coil thermostat has a differential between when the switch opens and closes of 4°–6°F. For example, if a heating thermostat is set at 65°F and the differential is plus or minus 3°F, the furnace will start when the greenhouse temperature drops to 62°F and shut off when it reaches 68°F.

Installation of an electronic thermostat with a plus or minus 1°F differential and using the same 65°F setting means that the furnace will start when the temperature drops to 64°F and heat until it reaches 66°F. If this concept is applied to a 30-foot-by-100-foot greenhouse heated with a fuel oil furnace to maintain 60°F in a northern climate, the savings of approximately 500 gallons per year (approximately 13% of the yearly fuel needs) will pay for the more accurate electronic thermostat in a couple of months. The savings in energy results from the lower heat loss from the greenhouse surface at the lower temperature.

Electronic thermostats have some additional benefits. The mercury or platinum sensor can be located up to 1,000 feet from the control box. Accurate visual readings show current and set-point temperatures on a digital display. A dial or key pad is used to adjust operating values. Most electronic thermostats will connect to 24-, 120-, or 240-volt equipment.

Controllers

A programmable environment controller is designed to integrate both the heating and ventilation systems. It will eliminate several thermostats and is designed to prevent system overlap. A typical example of overlap is when the heating system thermostat calls for heat while the exhaust fans are still running.

The microprocessor-based controller is a simple device that is reliable and accurate. All the components including switching relays are prewired and located in one waterproof box. The sensor, usually a thermister, can be located several hundred feet away.

The simplest controller is designed to provide heating and cooling system integration for a single greenhouse (figure 5-12). It has four cooling stages, a set point, and two heating stages. For example, cooling may start with a fan operating on low speed. If this can't keep up with the ventilation needs, the next stage kicks in and turns the fan on at high speed. Finally, if this can't keep up, a second fan could be activated. Motorized shutters or vents are opened as ventilation demand increases.

The same is true of heating. When heat is needed, one heater may be started. If the greenhouse temperature continues to fall, a second unit is activated. The set point is between the heating and cooling stage. At this point and at some of the other stages, horizontal air flow fans may be operating. The differential temperature between stages is adjustable.

Most units have day and night tem-

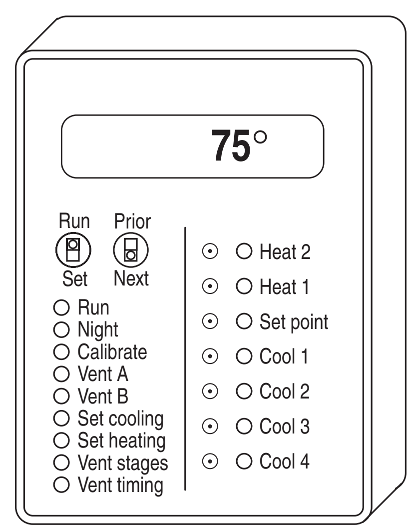


FIGURE 5-12. Typical step environment controller

perature settings and a night lockout that disables one or more cooling stages. An adjustable time delay between stages prevents rapid cycling of equipment. Other features include override switches, temperature display, indicator lights, and an aspirated sensor box. Controllers range in price from $500 to $1,500.

The next step above the basic controller is a unit that controls other environmental factors, including shade/heat retention curtains, lighting, and misting and irrigation systems. Most of these can be connected to a personal computer for central programming and system reporting.

Computers

Computer systems, although initially expensive, can help to reduce energy costs. With an incorporated weather station, a computer can anticipate weather changes and make adjustments in heating and ventilation systems. It can record environmental data that can be used in subsequent crops to get proper timing. The computer always knows what all systems are doing and, if programmed properly, can coordinate these systems to provide the optimum environment conditions.

Today's computers can control many environmental factors, including heating, ventilation, irrigation, carbon dioxide, and materials handling equipment. They can monitor electrical usage to prevent large surcharges based on demand.

Select accurate controls that will withstand the greenhouse environment and maintain their calibration. Be sure they are rated to carry the electrical load required to operate the equipment.

Maintenance

Keeping the greenhouse heating system in good operating condition can save money in several ways. Fuel consumption may be reduced as much as 20%. Heat distribution may be more uniform, resulting in a lower thermostat setting and better plant growth. The system is less likely to fail, which could result in crop losses.

A competent service person should clean and adjust all furnaces and boilers at least once a year, preferably in the fall before the heating season begins. The following checklist reviews the most important factors.

- ✔ Use the proper fuel. Using the wrong grade or type of fuel can result in carbon accumulations that will decrease heat transfer.
- ✔ Protect fuel oil tanks. Twenty percent of all service calls result from dirty fuel. Tanks should be away from dusty locations, and watertight fittings should be used. Tanks should be enclosed or protected to keep fuel from getting too cold.
- ✔ Remove soot from inside the furnace. A $^{1}/_{8}$-inch soot deposit can increase fuel consumption as much as 10%. Wire-brush and vacuum surfaces, or clean them with special cleaning compounds.
- ✔ Change fuel filters. Uniformly clean fuel delivered to the burner gives more efficient combustion. Fuel supply line connections should be tight. The oil filter should be replaced each time the furnace is cleaned.
- ✔ Use the correct nozzle size and angle. Excessive fuel consumption will result from too large or too small a nozzle. The spray angle should fit the shape of the firebox. Nozzles should be replaced yearly, because the hole becomes larger from wear, thus increasing fuel usage.
- ✔ Clean and adjust controls. Check gas valves, thermostats, and ignition mechanisms for clean, smooth operation. Inspect safety valves, low-water regulators, limit switches, and stack controls frequently.
- ✔ Lubricate oil bearings on motors and pumps. Periodic lubrication of bearings increases their life.
- ✔ Align belts. Check fan and blower belts for correct tension and wear. Replace as necessary. Clean fans and blowers.
- ✔ Maintain air filters. Clean or replace air filters to achieve maximum air flow.
- ✔ Ensure that water is clean. Drain off dirty water through drain cocks in steam and hot water systems. Flush steam boilers to remove scale and lime deposits. Analyze boiler water periodically to determine if treatment is needed.
- ✔ Monitor combustion efficiency. The lower the stack temperature, the higher the heat exchange efficiency; the higher the carbon dioxide content of the stack gases, the more completely the fuel is burned. Smoke and soot content of the flue gases should also be monitored.
- ✔ Replace oxygen. In poly houses and tight glass and fiberglass houses, install an air intake from outside to near the heater. Allow 1 square inch of intake area for each 2,000 Btu/hour furnace ca-

pacity. Replace existing heating systems with separated combustion units.

- ✔ Ensure that the chimney is high enough. The chimney should extend at least 2 feet above the ridge of the greenhouse. The top of the chimney should be at least 8 feet above the furnace to develop sufficient draft. Use a cap if necessary to prevent backdrafts and possible air pollution injury to plants.
- ✔ Ensure that the chimney is tight. Any air leaks will chill the gases and reduce the draft. Leaks can also allow plant-injuring flue gases into the greenhouse.
- ✔ Ensure that the chimney is the correct size. Follow the manufacturer's recommendation. Too small a cross-section or a chimney lined with soot will reduce the draft. Too large a diameter will cool the gases too quickly.
- ✔ Install baffles. Turbulators or baffles installed in boiler tubes slow down and direct the flow of gases so that more heat can be absorbed. Ten to 15% savings in fuel consumption can be realized.
- ✔ Install an automatic stack damper. This will help to keep the boiler warm between heating cycles.
- ✔ Check blower timing. In forced warm-air systems, operate blowers until the furnace is cooled to 100°–120°F or continuously where desired.
- ✔ Check radiator valves. These valves are vital to fuel savings. Repack leaky valves and replace defective ones.
- ✔ Inspect steam lines and steam traps. Repair all leaks in the distribution system and any damaged insulation. Make sure steam or hot water lines are not accidentally buried by debris or soil.
- ✔ Check radiators and pipes. Dust and dirt reduce heat transfer and increase fuel consumption, so keep components clean.
- ✔ Set the furnace and fan thermostat differential. Set the fan thermostat at least 10°F above the heater thermostat to prevent simultaneous operation and backdraft.
- ✔ Keep good records. Keep an inspection record of furnace maintenance for future reference.
- ✔ Inspect polyethylene tubes on unit air heaters. Inspect tubes regularly; replace when torn. Make sure the blower stays on after the heater or combustion unit stops. Delayed shutoff efficiently distributes heat and extends tube life.

Efficiency Testing

Efficiency testing of a furnace or boiler involves a simple ten-minute procedure and, if done on a regular basis, can pinpoint heating system problems early. Weekly records of temperature and carbon dioxide (CO_2) or carbon monoxide (CO) levels in the flue gases may indicate that carbon is building up on the heat-transfer surfaces or air leaks are developing in the combustion chamber.

Adjusting the burner to obtain 1–2% greater efficiency can significantly reduce fuel usage over the heating season. For example, a 2% increase in efficiency in a furnace or boiler heating a 30-foot-by-150-foot greenhouse will save about 200 gallons of fuel oil during the winter. This increase is quite realistic based on tests of a number of greenhouse heating systems in Connecticut a few years ago.

If heating units are maintained by a service person, ask for an efficiency test after the units are cleaned. If you maintain your own furnaces and boilers, it may pay to purchase a combustion test kit, which usually contains a stack thermometer that will read to 1,000°F, a carbon dioxide indicator with a sampling tube and calculator, a smoke tester and scale, and a draft gauge with a remote tube. Prices for these kits start around $285. See appendix C (page 77) for current manufacturers.

Before the heating season begins, the furnace or boiler should be cleaned and serviced. The burner blast tube, fan housing, and blower wheel should be free of dirt. Leaks into the combustion chamber, especially at joints between cast-iron boiler sections and around the fire door, should be sealed. The oil filter should be replaced and carbon removed from heat-transfer surfaces. Manufacturer's recommendations should be followed in replacing the nozzle and in adjusting the ignition electrodes.

On gas burners, servicing consists of cleaning the orifice, the burner, the heat-transfer surfaces, and the controls. Gas valves are checked for operation and leaks. Gas pressure is adjusted for the type of fuel used. The pilot light or ignition system is cleaned, soot is removed, and the fan and limit controls are checked for safety.

In the combustion process, air is mixed with fuel, which is heated. Excess air is always supplied to help with mixing and to provide carbon monoxide–free combustion. For oil units, a smoke test is conducted to reduce pollution. Unburnt carbon, collected on white filter paper, is compared to a calibration chart. A high smoke level indicates that the carbon in the fuel is not being burned and is escaping up the chimney.

On gas units, carbon monoxide in the flue can result from flame impingement on a cool firebox surface or from insufficient primary combustion air. It also produces a yellow flame that can be detected by the eye. The pressure setting of the gas valve should be checked, because excess pressure will give a smoky flame that accumulates soot on heat-exchange surfaces.

Combustion Test Procedure

1. Run the burner for a few minutes until operation has stabilized and the furnace or boiler is warm.

2. Set the draft. Although it is not directly related to combustion efficiency, the intensity of the draft governs the amount of air supplied for combustion and the rate at which the combustion gases pass through the firebox. Insufficient draft because of a leaky or too short chimney can increase the smoke level. Too much draft increases heat loss up the chimney.

   Check the draft reading over the fire with the draft gauge through a $^1/_4$-inch hole drilled in the fire or inspection door. Adjust the barometric draft regulator on the flue to the draft recommended by the manufacturer. If no recommendations are available, a setting of 0.02 inch of water column negative pressure is usually used. Where it is not possible to measure the draft at the firebox, a reading can be taken in the flue pipe near the furnace. An acceptable reading is 0.04–0.06 inch of water column.

3. Conduct a smoke test. Make a smoke measurement in the flue following the smoke tester instructions. Compare the spot on the test paper to the smoke scale supplied with the kit. A reading of 1 or 2 is acceptable. Readings of 3 or 4 indicate sooting and will require cleaning more than once a year. Tests have shown that a $^1/_8$-inch soot layer on heating surfaces will increase fuel consumption by more than 8%.

4. Conduct an efficiency test. A measure of the carbon dioxide content of the flue gases indicates how much heat from the fuel has gone to heat the greenhouse and how much is going up the chimney. A high carbon dioxide reading can result from excess air, poor fuel-air mixing, or poor regulation of the fuel input.

   Carbon dioxide is measured by a flue gas sampling device in which a known volume of gas is mixed with an absorbing solution. Combining this percentage value with the temperature of the flue gases at the same location and referring to a chart for the particular fuel burned in the furnace gives a steady-state efficiency value.

   Measure the stack temperature and carbon dioxide level following instructions with the test kit. Record these readings and the resulting combustion efficiency obtained from the chart or graph. Reduce the air gate opening on the burner blower slightly and repeat the efficiency test. This should increase efficiency. Check the smoke level to see if it is still acceptable. Repeat the test to obtain the highest efficiency while still maintaining an acceptable smoke level. On older units, the efficiency achieved should be greater than 70% for small burners and 75% for larger burners. With heat retention burners, efficiencies of 80% or greater should be obtained. If the efficiency recorded is much below the above recommended level, consider replacing the burner or possibly the furnace or boiler. The increased efficiency of a new unit should have a short payback with the current high price of fuel.

Heating System Modifications

Some modifications increase the efficiency of existing steam and hot water boilers. These include the addition of hot water mixing valves; automatic firetube cleaners; devices such as turbulators, which alter the flow within the firetube to increase heat transfer; and exhaust stack heat exchangers, which heat water using the exhaust gases.

Automatic mixing valves match the energy needs of the greenhouse with the temperature of the water in the heating pipe of hot water systems to help eliminate temperature surges and keep the greenhouse at a constant temperature. These valves, which are either three-way or four-way, are particularly useful where two water temperatures are needed, such as in floor heating systems. In this case, a maximum 100°F temperature is required in the floor, and variable temperatures up to 180°F are required in the overhead pipe loops (figure 5-13).

Automatic firetube cleaners blow periodic bursts of compressed air to remove soot from the firetubes. The tubes may be cleaned as frequently as once per hour. These cleaners eliminate the manual labor and downtime associated with hand cleaning. They save from 6% to 20% in fuel consumption and are ex-

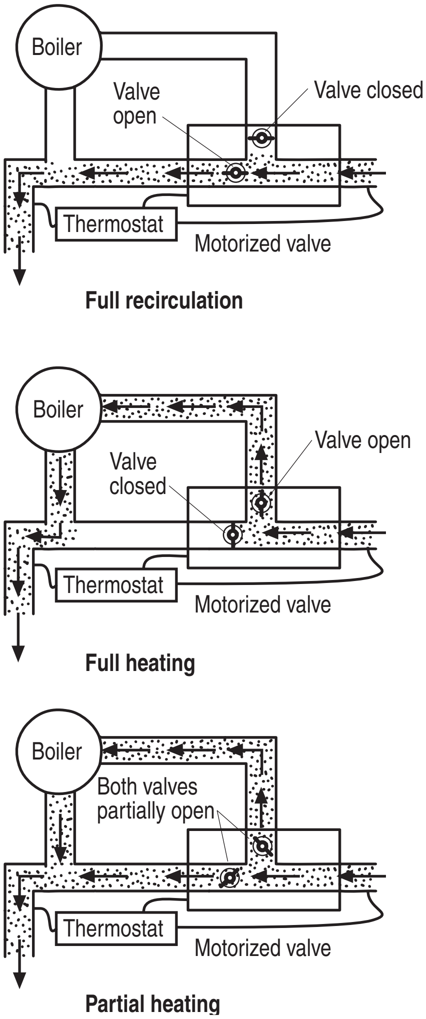


FIGURE 5-13. Heating system schematic showing automatic mixing valves

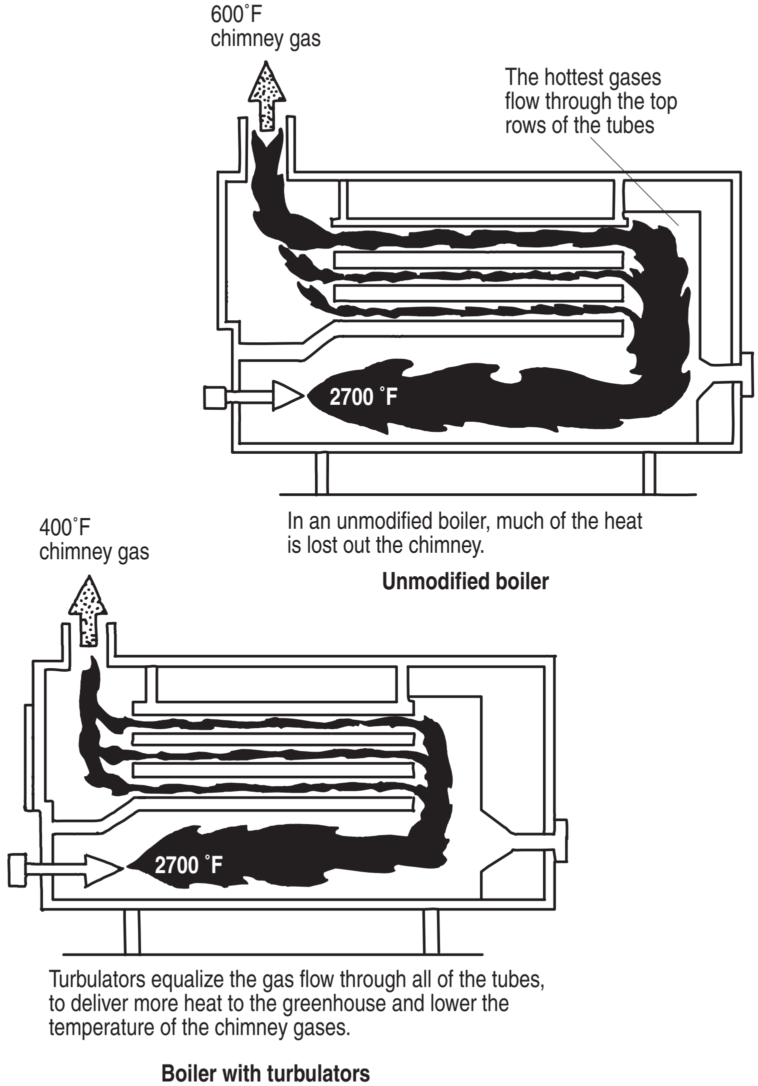


FIGURE 5-14. Turbulators increase boiler efficiency

tremely worthwhile for use with large boilers.

Turbulators are helical metal strips inserted into the firetube to create turbulence, equalize the gas flow through all the tubes, and increase the heat transfer across the tubes (figure 5-14). These must be removed when the boiler tubes are cleaned. Savings as high as 16% have been reported by some growers.

Exhaust stack heat exchangers can be used to supply hot water for soil heating systems or for heating irrigation water. These units transfer the energy in the exhaust gases (250˚–500˚F) to the water pumped through them. The exhaust temperature must be above 250˚F to eliminate the possibility of condensation and resulting corrosion.

Alternate Energy Heating Systems

Solar Energy Systems

Solar energy systems have been successfully designed and studied, but most have not saved enough fuel to provide a reasonable economic return. The energy-saving options previously discussed significantly decrease the quantity of fossil fuel required to heat greenhouses. Once these options have been installed, it is difficult to justify solar equipment, since fuel use may already have been drastically reduced.

Use of Normally Rejected Heat

A 3-acre complex designed with a floor heating system has been in successful operation for several years. The greenhouse is located 3,500 feet from a coal-burning electric generation station. Water flows from the cooling towers at 90˚–110˚F to and from the greenhouse complex through two underground 20-inch-diameter pipes. A $^3/_4$-inch polyethylene pipe heating system embedded in the rock floor storage distributes the heat throughout the 3-acre greenhouse. A loop also delivers warm water to two finned pipes under each greenhouse gutter, spaced on 28-foot centers (figure 5-15).

Cogeneration

The use of waste energy is very attractive, but it is limited to sites adjacent to power plants or industrial sites with 90°–100°F water available. Cogeneration systems may be installed almost anywhere, preferably near sources of methane gas, such as a landfill, an aerobic digester, or sewage treatment plant.

One type of cogeneration powers an internal combustion engine with natural gas, methane, or diesel fuel (figure 5-16). An electrical generator coupled to the drive shaft is connected electrically to the utility grid. Heat exchangers attached to the radiator and exhaust of the engine convert this energy to warm water, which heats the greenhouse. During research, about 25% of the fuel energy was converted to electricity and 50% to heat, for a total overall efficiency of almost 75%. The electrical energy is more valuable, so it is sold to the electric utility when it is not needed for greenhouse operation. Problems with the system include the initial high cost of the engine generator set and the daily maintenance of the internal combustion engine.

Another system uses solid-fuel, high-pressure steam boilers that drive a turbine. The electrical generator reduces the 100–150 psi pressure to the 5–10 psi pressure needed in the greenhouse heating system.

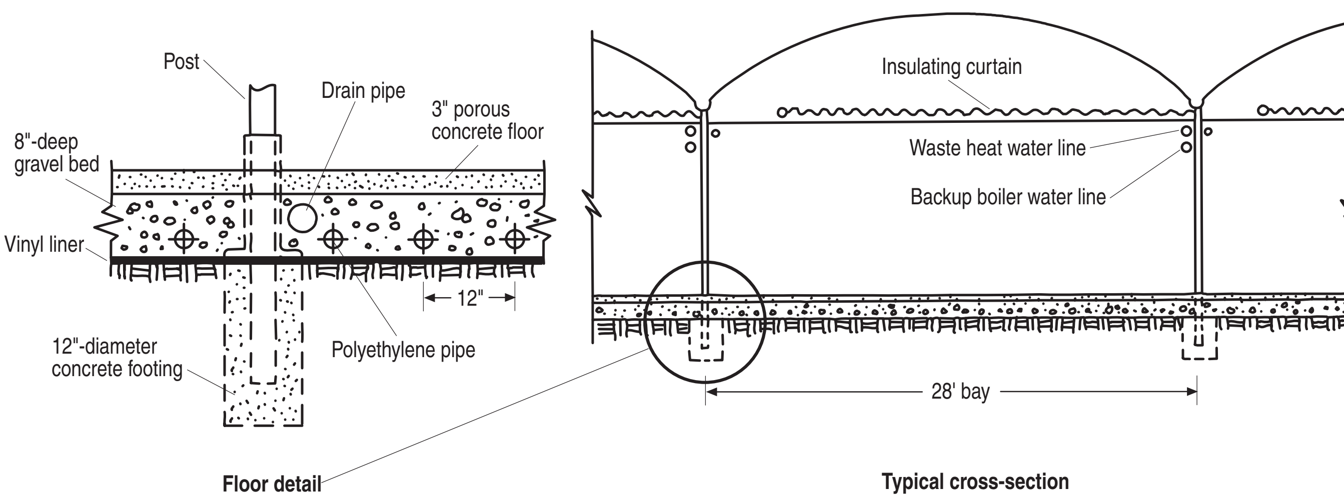


FIGURE 5-15. Heat distribution in a greenhouse using waste heat from an electrical generating plant

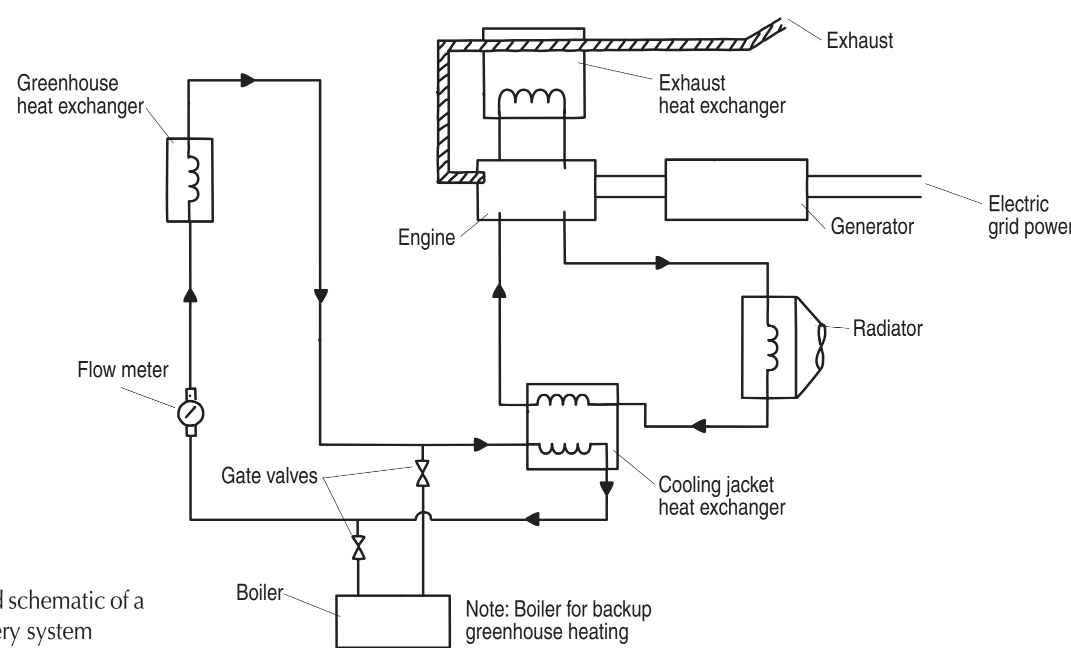


FIGURE 5-16. Simplified schematic of a cogenerator heat recovery system

6 Ventilation and Cooling

Greenhouses need ventilation to maintain optimum temperature, humidity, and carbon dioxide levels for plant growth. Ventilation reduces high temperatures caused by solar radiation by exchanging the inside air with cooler outside air. Plants also cool the air by transpiring water. A greenhouse filled with plants has a much lower cooling requirement than one containing only a few plants.

Greenhouse ventilation is accomplished either by natural air movement or by fans. Natural systems use temperature and wind pressure differences to move air through openings in the wall and roof. Fans create a pressure difference, drawing in air through louvers located on the opposite endwall or sidewall.

Natural Ventilation

Natural ventilation systems operate on the principle that heat is removed by a pressure difference created by wind and temperature gradients. Wind plays the major role. In a well-designed greenhouse, wind speeds of 2 miles per hour are adequate to keep the inside temperature within two degrees of ambient. For most locations, there are very few days that the wind is less than 2 miles per hour, especially if the outdoor temperature is above 80°F.

Buoyancy, the effect from heated air rising, also aids ventilation. The trend toward taller greenhouses has helped, because the increased height drives the buoyancy forces.

Shade is also important to reduce the heat load on the greenhouse and the need for ventilation. Exterior shade is best, as it keeps the heat out. A retractable system, shade fabric, or shade compound can be used. Interior shade is less effective, as the heat enters the greenhouse and has to be removed. White or black porous shade fabric or an aluminized material that allows good air movement is commonly used.

Natural ventilation systems reduce energy costs but are less controllable. Fan ventilation can use 0.5–1 kilowatt-hour per square foot of greenhouse floor area per year.

Design Guidelines

Research at Ohio State University's Ohio Agricultural Research and Development Center in Wooster has shown the following design considerations to be important for the best operation of natural ventilation systems:

- A greenhouse should be orientated to intercept the normal summer wind along the side. Trees and buildings should not obstruct the natural air flow.
- The windward sidewall should have no sharp edges, such as a gutter, that will deflect air high over the greenhouse. Adding a curved half-span section with a side vent to a gutter-connected greenhouse improves the air pattern.
- For best results, windward side vents should be located near the ground and be larger than the area of one roof vent.
- In a greenhouse with conventional roof vents, the vents should be 15–20% of the floor area and open leeward to the wind.
- Seals around vents should be designed to provide tight closure.
- Horizontal air flow (HAF) should not be operated when natural ventilation is being used.
- Insect screening, if desired, must be sized to keep air flow restrictions low.
- Computer control for maintaining the environment and opera-

tion of the vents is highly desirable. A computer can be used to anticipate rain and high winds so the vents can be closed.

Most greenhouse manufacturers have naturally ventilated designs. Some of the basic systems are reviewed below.

Roll-Up Sides

One of the least expensive systems is the roll-up or drop-down curtain design. It can be fitted to most hoophouses (figure 6-1). These systems work best during the late spring, summer, and fall. Thermostatically operated fan ventilation may be needed during the cold weather, when only a little cooling is needed.

Both manual and motorized systems are available. The ventilation rate is controlled by the size of the opening. The drop-down system works better in cooler weather, as the air is introduced above the plants. Guides are installed to keep the detached sidewall curtain from blowing on windy days.

Roof and Sidewall Vents

The rack-and-pinion mechanism is a common device for opening roof and side vents. It gives positive positioning and can be adjusted in small increments.

In freestanding greenhouses, vent openings should be provided on both sides of the ridge and on both sidewalls (figure 6-2). Vent operation should be such that the leeward vents are opened to produce a vacuum at the top of the ridge. The combined sidewall vent area should equal the combined ridge vent area, and each should be 15–20% of the floor area.

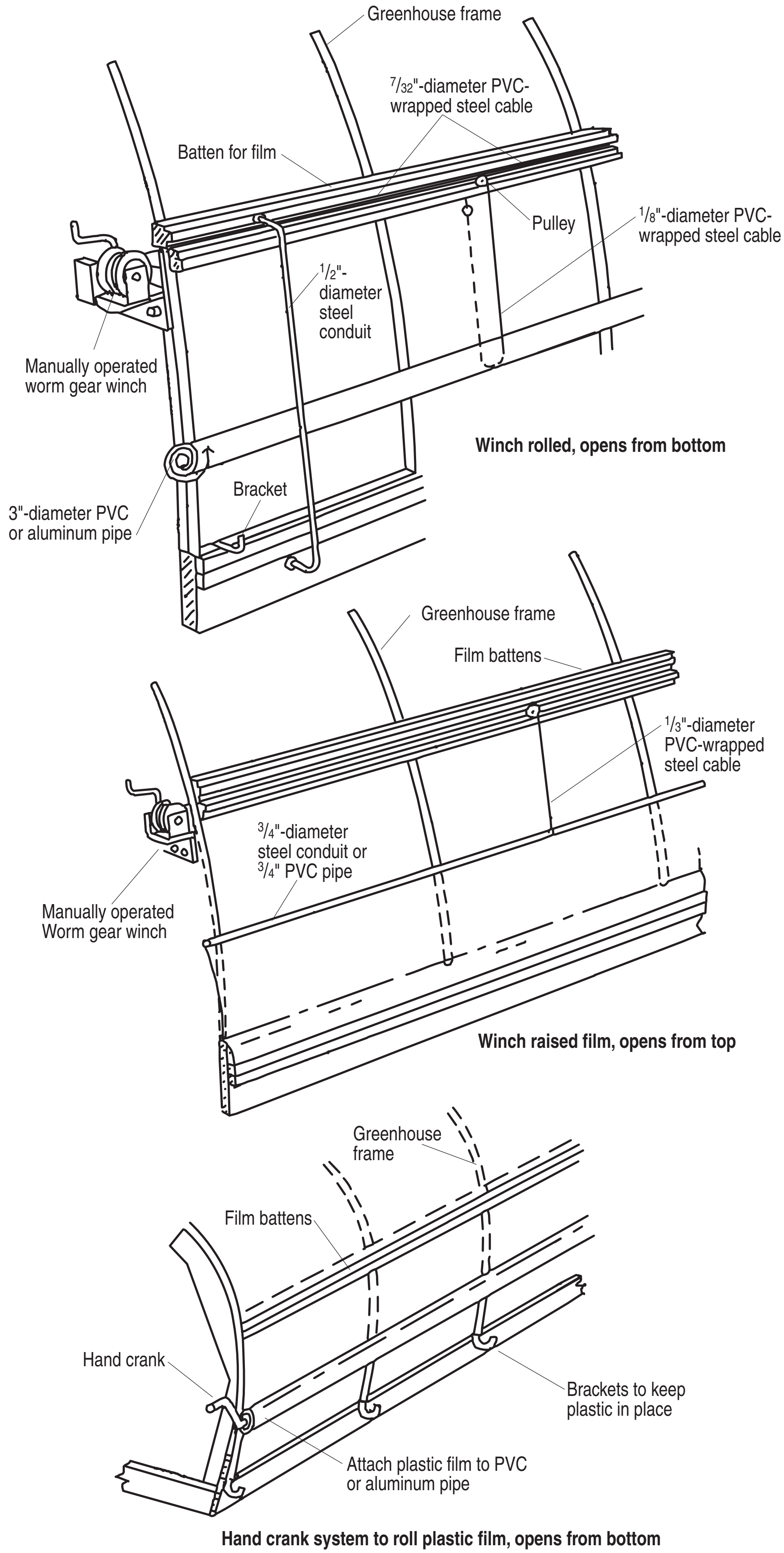


FIGURE 6-1. Manually operated ventilation walls

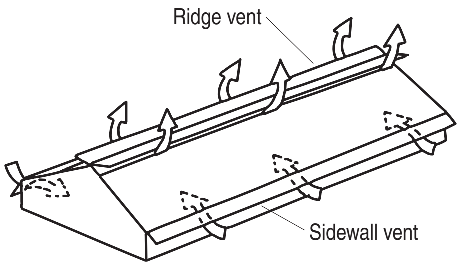


FIGURE 6-2. Natural ventilation with ridge and sidewall vents

Research has shown that in gutter-connected houses, it is more efficient to have the ridge vents open several feet above the gutter rather than at the gutter. This also prevents freeze-up of the vent during the winter. A windward sidewall vent will provide most of the intake air.

Distribution of heated air removal may not be uniform, with more air leaving through the roof vents farthest from the intake. But in a well-designed greenhouse, the temperature at crop level should be no more than 5°F above ambient. In large gutter-connected greenhouses, both cool intake air and hot exhaust air will flow through the same roof vents.

Roll-Up Roof

Several manufacturers make a roof that rolls up on a shaft that runs the length of the greenhouse bay. Single- and double-poly systems are available. A light, second framework over the structure secures the plastic from billowing out during windy weather. The roof can be opened and closed manually or automatically.

Retractable Roof

Flat or low-profile retractable roof systems using cable technology are available with porous or nonporous coverings. They are low-cost ($0.75–$4.00 per square foot) and can be erected quickly. Designs are available that will take a heavy snow or wind load. Heating this type of structure can cost 30–40% more than heating a double-layer poly house.

The roof material, supported on horizontal cables, can be retracted to expose the plants to direct sunlight and outdoor temperatures. These structures are becoming popular for overwintering or hardening off plants in northern climates.

Open Roof

Open-roof greenhouses work well in snowy climates, as they can be tightly closed during cold weather (figure 6-3). Most designs use standard vent hardware. Some have panels hinged at the gutter that rotate upward. Others have panels that are hinged at the ridge and one gutter and slide sideways on Teflon bearings. Most designs use rubber gasketing to seal the joints. Glazing can be glass, polycarbonate, or film plastic. Some manufacturers provide a small gutter to collect rainwater when the roof is partially open. Growers with these greenhouses report very uniform summer temperatures, higher light levels, and excellent crops.

Fans

Fans are normally mounted in one wall, and matching inlets are located on the opposite wall (figure 6-4, page 42). In greenhouses with ridges oriented north-to-south, fans should be mounted in the north wall and the inlets placed on the south wall. If prevailing summer winds come from

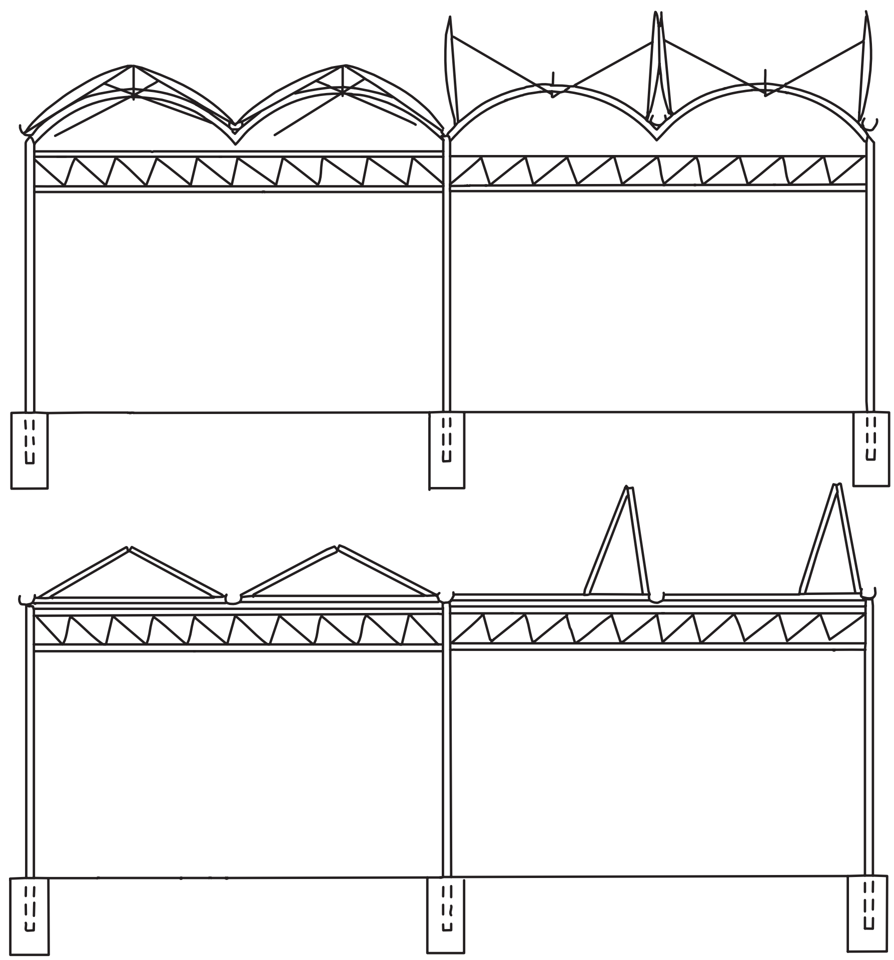


FIGURE 6-3. Folding roof designs provide natural ventilation and increased sunlight

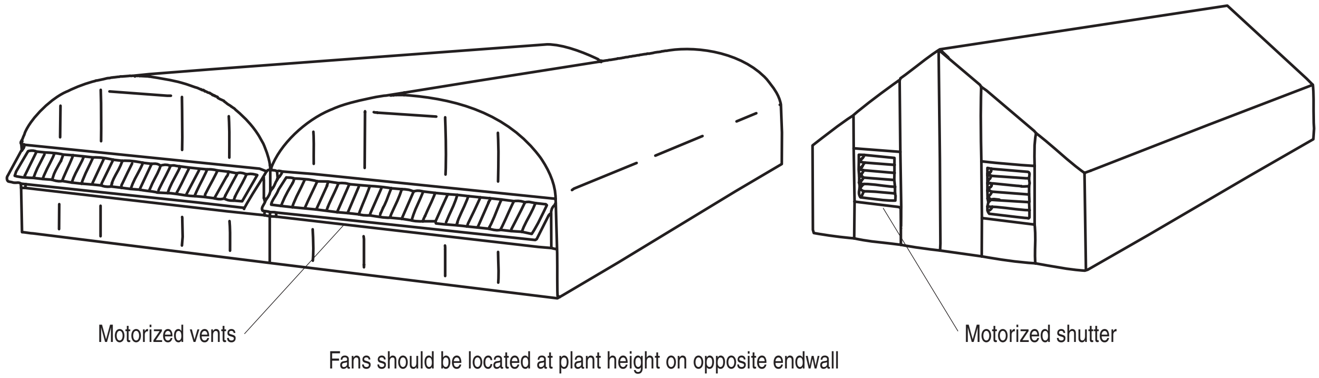


FIGURE 6-4. Motorized inlet vents

the north, place fans on the south wall. Having fans operate with the prevailing wind will increase their effectiveness by about 10%.

Install enough fans to provide 8 cu-bic feet per minute per square foot of floor area for a greenhouse with an energy/shade curtain and 10 cu-bic feet per minute per square foot of floor area for a greenhouse without a curtain. This ventilation rate results in a 5°–12°F increase in air temperature from the intake end to the exhaust end in the worst summer conditions. Increasing the rate of air exchange does little to reduce the temperature and only increases the energy costs. The distance between inlet to outlet should not exceed 200 feet. In cases where auxiliary cooling methods are used, as much as 275 feet between fans and inlets may be appropriate.

Select fans that develop the required flow at 0.1–0.125 inch static pressure water gauge at minimum horsepower. Large-diameter fans are more energy-efficient and can be grouped in large greenhouses to give at least three flow rates. Well-designed fans will deliver 18,000–20,000 cubic feet per minute per horsepower. Propeller fans efficiently move large volumes of air against low static pressures and are best for most greenhouse applications.

When purchasing new fans, select those that have been tested in accordance with Air Movement and Control Association (AMCA) standards. Fan output varies considerably among manufacturers and individual models. Also compare the ventilating efficiency ratio (VER), which is the ratio of the volumetric rate of air movement to the rate of energy consumption. This varies from about 10 to 20 cubic feet per minute per watt. Purchase fans that have a VER of 15–20.

Undersized fans do not effectively control the environment. Oversized fans cost more to operate, require a high initial investment, and create excessive air velocities. Air velocities of more than 200 feet per minute may have a detrimental effect on plant growth.

Controls

Capillary bulb thermostats or electronic thermisters mounted in an aspirated cabinet usually control multifan systems (see figure 5-10 on page 32). The first temperature setting turns on 10–15% of the installed capacity, usually one or two fans on low speed. If additional cooling is needed, about 40% of fans are activated for a second stage. In a three-stage system, all the fans are operated for the third stage (table 6-1). In each case, a controller wired to the sensors maintains the vent opening relative to the number of fans running to produce an apparent velocity of about 700 feet per minute through the vents.

A better system utilizes a differential pressure switch/gauge to sense inside static pressure compared to outside atmospheric conditions and adjust the power-operated air inlet vents. This maintains the required negative pressure in the building to ensure proper ventilation. Temperature sensors also provide input to the computer or controller to adjust fan speed as necessary depending on indoor and outdoor air temperatures.

TABLE 6-1. Example of staged fan system operation with an installed capacity of 21,200 cubic feet per minute (cfm)

Stage	Fan #1 24-inch — 3,200 cfm	Fan #2 36-inch — 9,000 cfm	Fan #3 36-inch — 9,000 cfm
1	on	off	off
2	off	on	off
3	on	on	on

Ventilation is important during the winter, particularly in double-glazed structures, to make sure enough carbon dioxide is available to the plants and for humidity control. The cool air entering the greenhouse must thoroughly mix with the inside air, or cold spots will occur near the intake. A slot inlet mixes the cold outside air with the inside air in a long, narrow jet. The controller activates the window drive, depending upon the number of thermostats calling for ventilation (figure 6-5).

Motorized shutters (figure 6-5) are an alternate method of controlling inlet air, especially in small greenhouses. Plan for 1.5 square feet of air inlet opening per 1,000 cubic feet per minute of fan capacity. Place the shutters so that air does not hit the plants directly. Both gravity and motorized shutters should be linked together and have nylon or brass bearings for low maintenance.

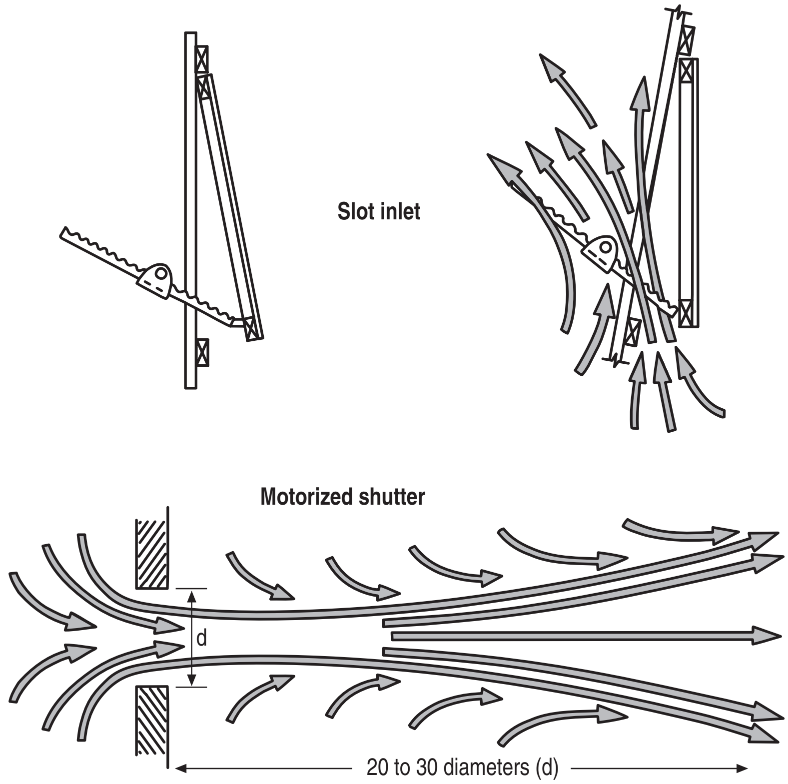


FIGURE 6-5. Air distribution patterns through a slot inlet and motorized shutter

Maintenance

Check fans, motorized shutters, and the control system for proper operation. Good maintenance of the ventilation system can save 10–20% of fan energy use. Use the following checklist as a maintenance guide:

✔ Check fan and motor bearings for overheating. Lubricate or replace as required.

✔ Check pulley sheaves for correct alignment. Shafts should be parallel, and edges of sheaves should line up on a straight edge.

✔ Shiny pulley sheaves indicate a loose belt. Refer to the installation manual for proper tension. Usually a properly tensioned belt will deflect 3⁄4–1 inch at the center. Slack belts wear excessively, cause slippage, deliver less power, and may cause belt breakage. Excessive tension can cause bearing wear and possible pulley failure.

✔ Keep belts clean, free of oil, and protected from sunlight as much as possible. Mineral oil is especially destructive to belts. For normal cleaning, wipe belts with a dry cloth. The safest way to remove excess dirt and grime is to wash with soap and water and rinse well. Never use a belt dressing on a V-belt drive.

✔ Remove dust from fan blades, housings, and shutters to prevent fan vibration and to provide an unobstructed air flow. Excessive fan vibration will reduce air flow and stress the bearings.

✔ Check gravity louvers for free operation and tightness of seal when closed.

✔ Remove weeds and shrubs growing outside the greenhouse that block fans and interfere with louver operation.

✔ Check fans for proper rotation. Fans can be accidentally reversed if wires are switched during repairs or modifications. Reversed fans will move some air and may not be readily detectable.

Decreasing Energy Use in Mechanical Ventilation

Several methods may be used in conjunction with fans to control temperatures during periods of high solar intensity and high temperature. These include the use of thermal blankets as a variable shade system, fixed shading, evaporative cooling, misting, and irrigation.

Shading

Shading will reduce the amount of the sun's rays that enter the greenhouse and therefore reduce the internal temperature and light level. Two basic methods of greenhouse shading are internal and external.

Internal shading can be fixed and supported on a wire or frame above the crop. It can also be retractable and supported on monofilament or cable above the energy truss. Several materials, including polypropylene, saran, polyethylene, and polyester, are available. Shade fabrics with aluminum foil strips work the best in many greenhouses, as the aluminum reflects the sun's rays back through the glass before it turns to heat.

An external system, where the shade is outside the greenhouse, is better in that the sun's rays are reflected before they enter the structure and turn to heat. Also, the shade material does not get in the way as it sometimes does with an internal system. Most of the shade materials described above can be used on the outside. Pieces are sewn together, edges reinforced, and grommets added to make a cloth large enough to cover the greenhouse roof area. Rope or tie-downs will hold it in place.

Research at North Carolina State University has shown that misting the shade cloth on the outside of the greenhouse can significantly reduce the amount of fan operating time. A PVC line, containing micro-irrigation nozzles spaced about 5 feet apart, located on each side of the ridge of a poly-covered hoophouse and operated 30 seconds out of every 3 minutes gave excellent heat reduction in the greenhouse.

Shading compounds that are brushed, rolled, or sprayed onto the glazing work well on glass. The level of shade can be varied by the amount of compound applied. Shade material is more difficult to remove from film plastic glazing.

Evaporative Cooling

Evaporative cooling, which uses the heat in the air to evaporate water from leaves and other wetted surfaces, can be used to cool the greenhouse to below outdoor ambient temperature. It takes 1 Btu of heat to raise the temperature of 1 pound of water 1°F, but it takes 1,060 Btu's to change the same amount of water to a vapor. Using this principle, large amounts of excess heat can be removed from the greenhouse.

With an evaporative cooling system, humid air containing all of the heat that is picked up is exhausted out of the greenhouse, and drier, cooler outside air is brought in. Evaporative cooling works best when the humidity in the outside air is low. These conditions are most common in the dry Southwest, but even in the more humid northern sections of the United States, significant evaporative cooling can occur most days in the summer.

In the most common system, outside air is drawn through and cooled by a porous, wet pad. The pads, mounted either horizontally or vertically, are made with treated corrugated paper (figure 6-6). A perforated pipe distributes water over the top of the vertical pad, and a gutter beneath catches the water for recirculation. Vertical pads require considerable maintenance to remain effective. These pads tend to settle, leaving holes for uncooled air to pass through, or they decompose and clog the water recirculation system.

Horizontal pads have been developed as low-cost cooling systems, but they require more space than vertical pads even when the pads are stacked two or three high. The open horizontal pad is simple to repair or replace. Nozzles spray water mist over the pad, and some do not recirculate the water. These advantages simplify maintenance and make horizontal pads energy-efficient.

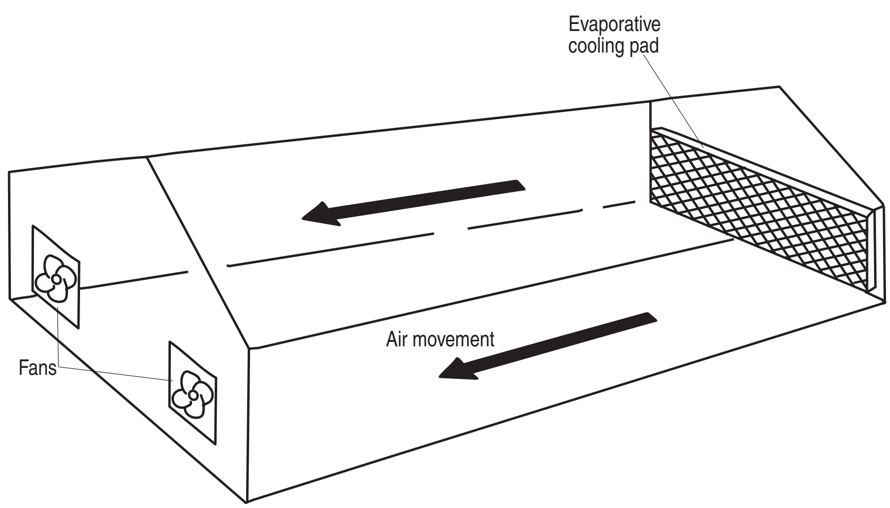


FIGURE 6-6. Vertical evaporative cooling system

Fog

Some cooling systems use high-pressure nozzles to form fine water droplets (figure 6-7). Fog eliminates free water problems and provides adequate cooling and humidity. Water at very high pressure (500–1,200 pounds per square inch) will form a fog that envelopes the greenhouse. High-pressure piping and equipment are necessary, and maintenance is demanding. Particular care has to be given to filtration to prevent nozzle clogging. Some systems minimize this problem by using high-pressure air (60–80 pounds per square inch) to fog low-pressure water. These systems are expensive, since large-capacity air compressors are required to provide the needed air volume.

Both evaporative cooling and fog systems cool effectively. No studies have shown that one method is more effective than the other. Both systems will carry any minerals in the water, however, which can coat and discolor plant surfaces.

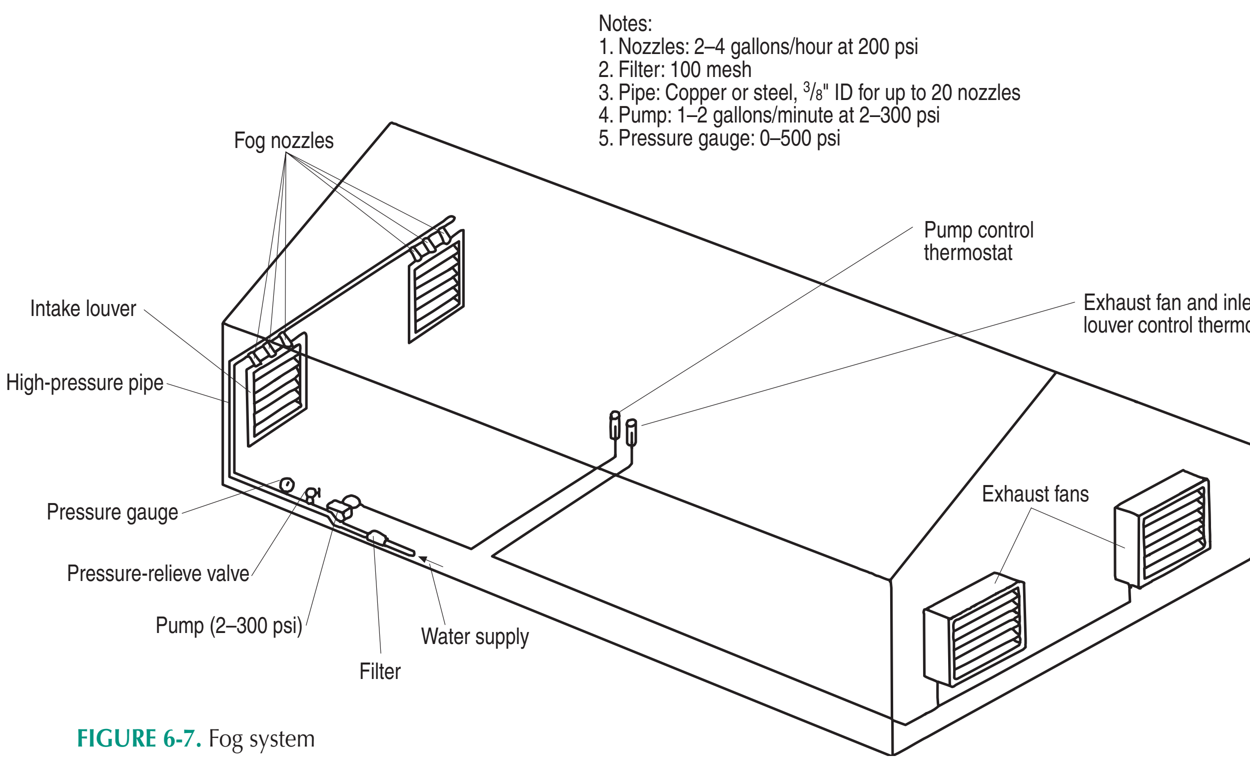


FIGURE 6-7. Fog system

7 Space Utilization

One excellent way to reduce the energy cost per plant is to make more of the greenhouse space available for production. Traditional greenhouse bench layouts utilize 60–70% of the floor area for plant production. Peninsular layout of stationary benches with a single wide center aisle and many smaller ones perpendicular to it between the benches can increase the amount of usable space to over 75% (figure 7-1).

Movable Bench Systems

Movable growing systems can increase the production area to over 90% of the total greenhouse area. Figure 7-2 compares space utilization between typical conventional and movable bench systems.

Movable benches are used mainly for potted plants. Bedding-plant production systems, where plants are grown in flats on the floor, and flooded-floor systems for potted plants usually achieve over 90% space utilization. Because accessibility is restricted, moving benches are generally not recommended for potted plants that require daily maintenance or in retail sales greenhouses.

The two types of moving growing systems are moving benches and transportable trays. In both systems, over 90% of the space is available for plant production. Though the initial investment is significant, labor efficiency can be greatly enhanced, and the energy use per plant is reduced.

Movable Benches

The simplest movable bench system to install has benches that remain in the greenhouse but move on rollers placed over a supporting frame to provide aisle space (figure 7-3). A worker turns a crank or pushes and rolls the benches sideways, opening an aisle between adjacent benches. The bench layout can be across either the length or width of the greenhouse. In greenhouses longer than 100 feet, a crosswise direction may be more convenient to reduce the length of the aisle and the distance plants have to be moved (figure 7-4).

Normally, bench tops are 30–36 inches above the floor. For crops such as tomatoes and cucumbers, or where a floor heating system is installed, movable benches can be supported near the floor (figure 7-5, page 48).

Problems associated with movable benches include limited maneuverability in the aisles. Placing or removing plants can be accomplished with a narrow belt conveyor that folds for transport. The conveyor is placed in the aisle between the benches, and plants are loaded or unloaded by hand.

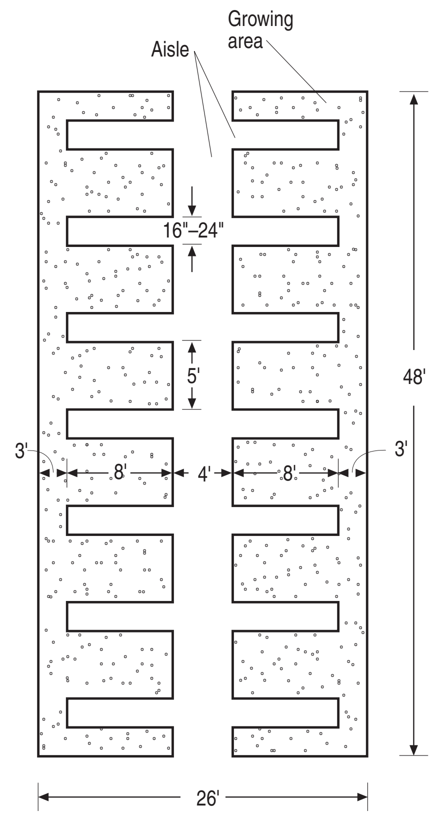


FIGURE 7-1. Typical peninsular bench layout for a greenhouse

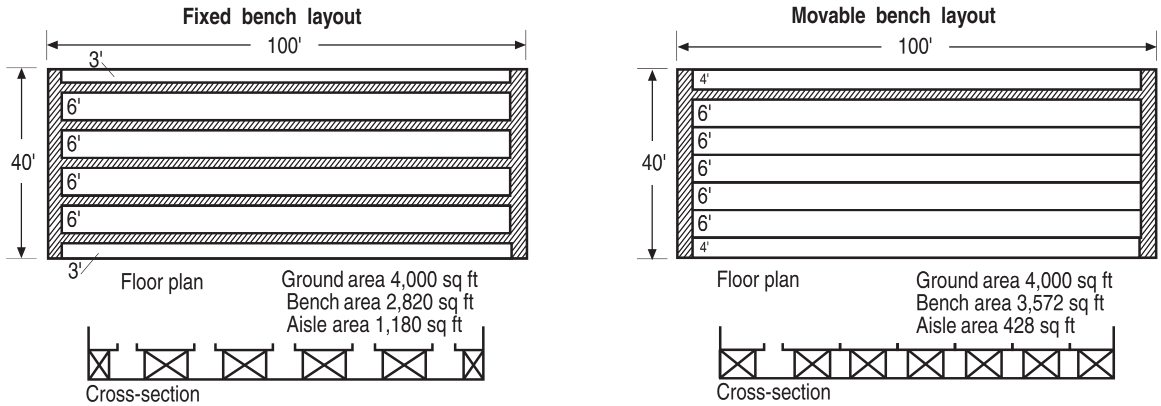


FIGURE 7-2. Usable space comparison between conventional and movable benches

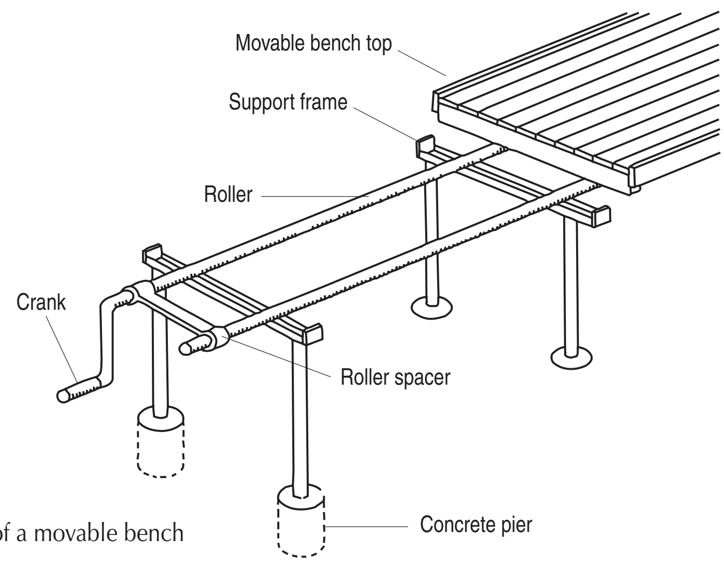


FIGURE 7-3. Parts of a movable bench

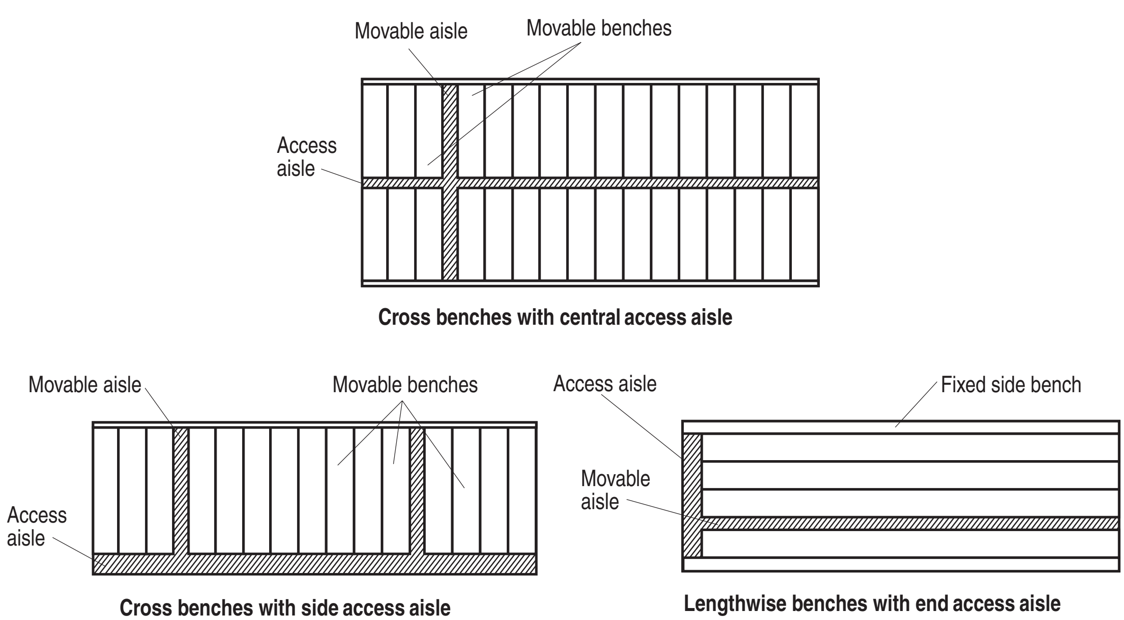


FIGURE 7-4. Common movable bench layouts

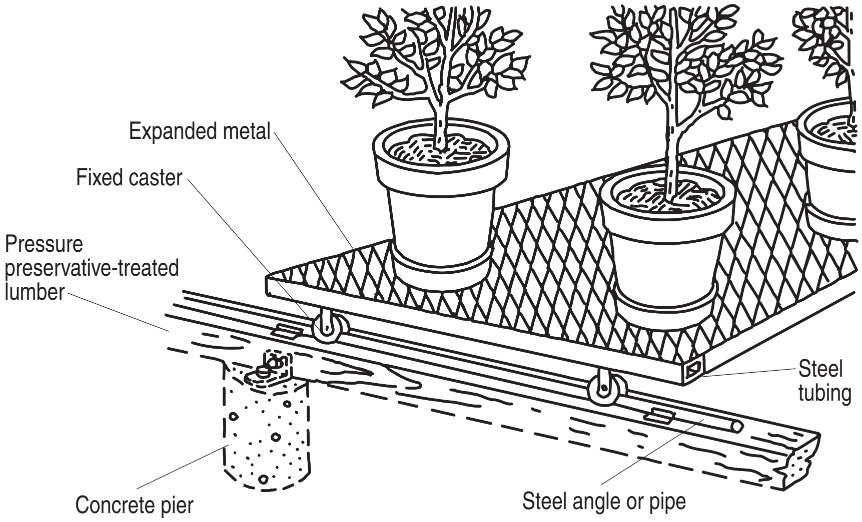


FIGURE 7-5. Floor-mounted movable bench for tomatoes, cucumbers, or stock plants

An alternate method uses a trolley conveyor (monorail) supported from rails attached to the greenhouse structure. Typically, a worker opens the appropriate aisle and pushes or pulls the overhead carrier along the aisle. Plants are placed on the carrier and pushed to the sales or headhouse area. The greenhouse structure must be strong enough to support the weight of the plants placed on any overhead carrier.

Tray Systems

A more complex installation uses modular trays that move sideways to create a work aisle and lengthwise for removal to the work area. All transplanting, pot filling, pinching, and other necessary operations are handled in the work area as the trays move in front of workers in assembly-line fashion (figure 7-6).

The trays are moved to and from the growing area manually on rails or carts or mechanically on conveyors. Because tray systems are more expensive than movable benches, they are economical for crops that remain on the benches for less than four months or crops that require frequent spacing, pinching, disbudding, and so on.

Design of Movable Bench Systems

The standard widths for movable bench tops are 5, 5.5, and 6 feet. This allows access to the center from both sides and allows enough bench movement to get adequate aisle space without the bench tipping off the rollers. Benches 4 and 4.5 feet wide have been used, but they limit the aisle width to 16 inches or less if rollers are used. Narrower benches work if supported by casters or roller conveyors.

Tray bench tops are available from manufacturers in several sizes (5 feet by 6 feet, 6 feet by 8 feet, and 6 feet by 10 feet). Other sizes as wide as 8 feet and as long as 40 feet have been fabricated by some growers. In selecting a bench width, consider the crop to be grown and the size of the bench that would conveniently fit into the greenhouse area.

Bench Materials

Open-bottom benches are commonly used with potted plants and bedding plants, since they allow air circulation and water runoff. This reduces insect and disease problems.

Galvanized expanded metal makes a strong bench surface. Standard diamond-design ($^3/_4$-inch, 14-gauge) material does not sag or stretch when properly supported. An F-shaped aluminum extrusion is available to enclose the edges.

Welded wire mesh is a low-cost material that tends to sag and create an uneven surface. If used, staple $12^1/_2$- or 14-gauge mesh to a wood framework and cross-brace a minimum of every 2 feet.

Another option includes ebb-and-flood, lightweight molded plastic or

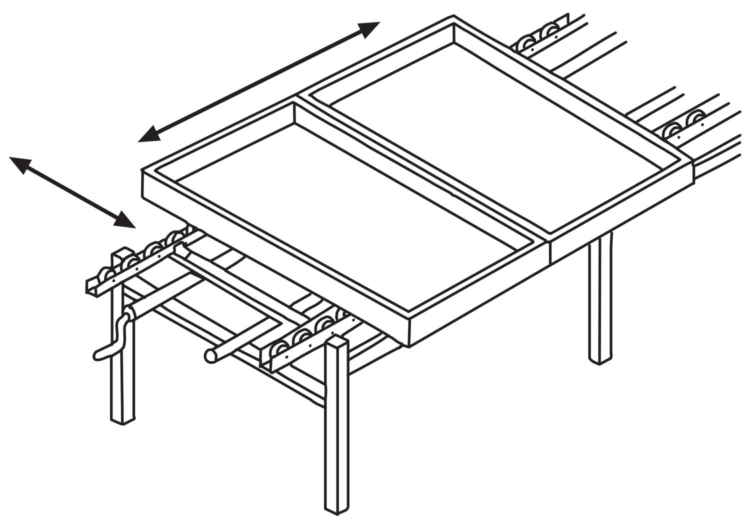


FIGURE 7-6. Tray or pallet movable bench with wheel conveyor

reinforced fiberglass trays. Some growers have developed movable benches to support ebb-and-flood troughs.

Movable Bench Support Systems

Steel pipe or tubing is the most common material for the bench frame. Pipe or tubing 1.5–2 inches in diameter is usually fabricated from commercially available bench fittings. Steel angle or channel (1.5–2 inches) can also be used. To reduce friction and provide easy movement of the benches, the bearing surfaces should be metal. Wood framing is rarely used unless support surfaces are covered with steel strapping.

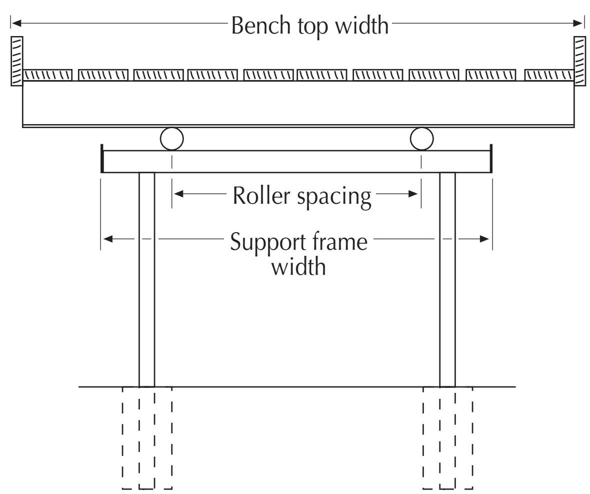
The support frames should be anchored to the ground with concrete piers (8 inches in diameter by 12 inches deep) or set on the edge of the concrete walks. Lateral and diagonal bracing are needed on unanchored frames.

It is important that the tops be level and in line. If not, they will tend to roll to one side, making it difficult to keep the aisle open. Depending on the plant load, the frames should be spaced from 5 to 10 feet apart. Benches should be designed to support a load of 25 pounds per square foot. A sand rooting bed deeper than 3 inches will require greater support.

Spacing of the rollers and width of the top of the support frame are critical for adequate bench support and clear aisles. Table 7-1 gives typical dimensions for several bench sizes and aisle widths. It is important to maintain a ratio of 2:1 for supported to unsupported bench width to keep the bench from tipping when it is in the fully extended position.

TABLE 7-1. Dimensions for movable bench layout

Bench top width (feet)	Aisle width (inches)	Roller spacing (inches)	Support frame width (inches)
4.0	16	22	32
	18	20	31
	20	not recommended	
4.5	16	28	38
	18	25	36
	20	22	34
	22	not recommended	
5.0	16	32	42
	18	30	41
	20	28	40
	22	25	38
	24	not recommended	
5.5	16	32	42
	18	32	43
	20	32	44
	22	32	45
	24	28	43
6.0	16	32	42
	18	32	43
	20	32	44
	22	32	45
	24	32	46



Movable Bench Costs and Returns

A movable bench system has an initial cost of $4–$5 per square foot of bench. Tray systems cost up to $6 per square foot installed. If it is possible to increase space utilization by 20% with moving benches, that corresponds to a 20% decrease in energy cost per unit. If yearly energy costs are $2.50 per square foot, at least $0.80 per square foot is available each year to pay for the investment.

The biggest gain with movable growing systems is the increase in worker productivity. The two savings taken together ensure the value of the investment.

Heated Floor Growing Systems

Growing on heated concrete floors offers space utilization comparable to movable growing systems for crops that need to be placed on the floor only once and picked up once. Examples include flats of bedding plants in the spring and potted poinsettia plants in the fall.

Some growers place potted plants on the floor as they would on a large bench. They are then picked up as needed, placed on a conveyor, and run on an assembly line in front of the workers, eliminating much of the stoop labor. The initial cost is lower than a movable bench system, and the management options are greater since the greenhouse is totally open for many crop-growing arrangements. Because the plant canopy remains several degrees warmer than the temperature at the 5-foot level, the nighttime air temperature can be reduced 5°–10°F. This lower operating temperature reduces heating costs significantly.

Combination Floor and Movable Bench System

A unique combination of both movable benches and floor heating has been developed. The system includes a floor heating system and a transportable tray system located 20–30 inches above the floor (figure 7-7). Two crops are grown: one on the floor, and another on the trays. During the day, the trays are rolled outside of the greenhouse onto a matching pipe network. Both crops receive full sunlight. At night, they are rolled back into the greenhouse. In severe weather, the bench crop is not moved outside, and the floor crop receives minimum light. This system can be adapted to both hoophouses and gutter-connected houses. The system is good for hardening off bedding plants during the spring and for potted plants during the summer and fall.

Rack Growing

Installing racks in the greenhouse can double the growing space. They are most effective where foliage plants are grown, creating conditions similar to a forest canopy. Plants requiring the most light are placed on top of the rack, and those that require the least light are placed at the bottom. Many ingenious arrangements, including slanted racks and racks that can be moved to the work area, have been developed (figure 7-8).

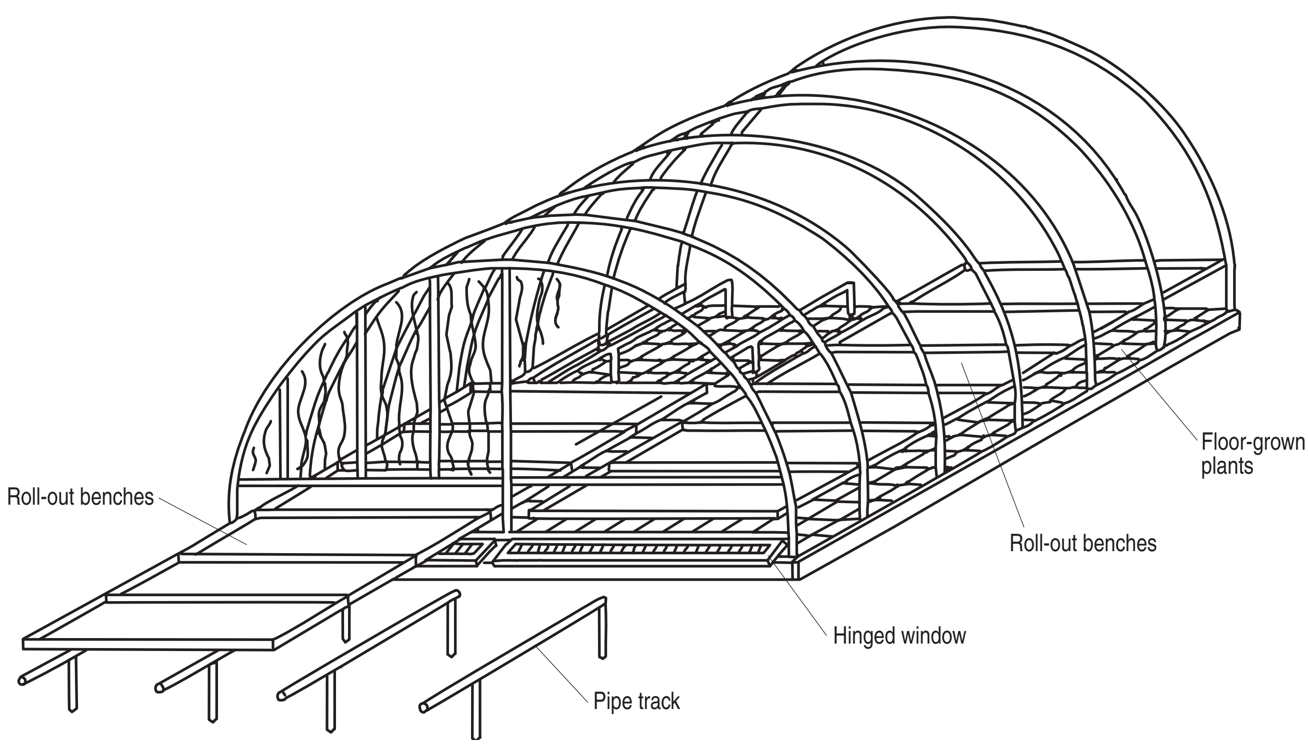


FIGURE 7-7. Roll-out bench system for a hoophouse

Hanging Baskets

Many growers hang baskets over part of their growing area. These baskets are fitted with automatic watering systems, and the spacing depends upon the light requirements of the crops on the floor or benches beneath. Normally, two rows of baskets every 20 feet will not adversely affect the crop underneath.

Hanging basket conveyor systems attach to the overhead trusses in the greenhouse. Plants spaced as close as 8 inches apart are supported by a cable that moves them past work and watering stations. The convenience of having plants brought to the end of the greenhouse for inspection and shipping can offset the cost of the system. Because plants change location, they are exposed to more uniform daily light, which enhances growth. See appendix C, page 77, for a supplier.

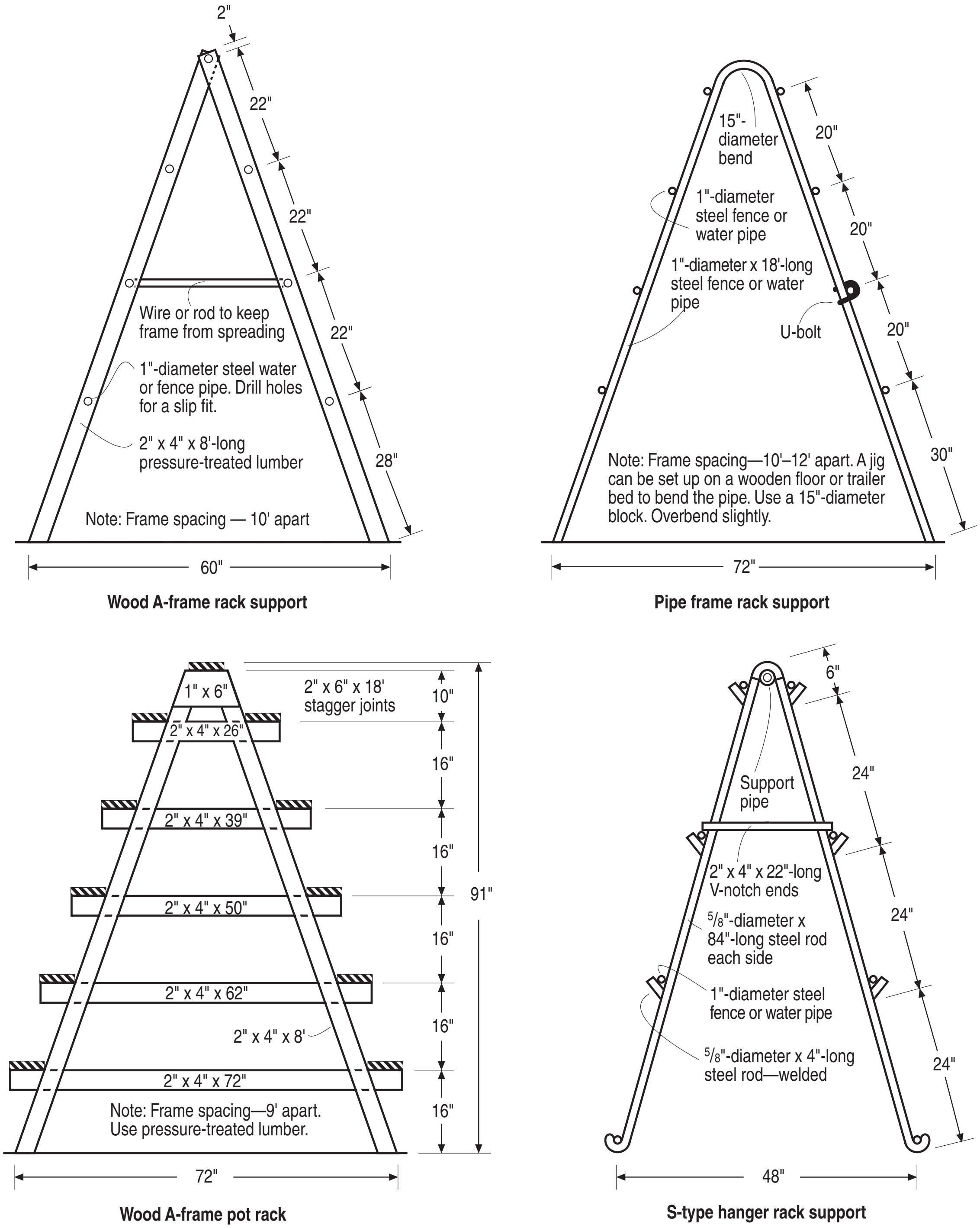


FIGURE 7-8. Greenhouse rack systems

8 Utilities—Electricity, Lighting, and Water

Utilities play an important part in the operation of greenhouses. Significant savings can be made with proper installation and maintenance.

Electrical Systems

The greenhouse environment is one of the harshest for electrical equipment. Rust and corrosion from high humidity, dust, and chemicals affect the operation of moving parts and electrical contact surfaces.

Electrical Code

The National Electrical Code (NEC) is the minimum standard for wiring installations. Some states and local municipalities have more restrictive regulations. In many areas, an electrical permit is needed to install or do work on a system. This is available from the local building official. Compliance with the codes is important in meeting Occupational Safety and Health Administration (OSHA) and insurance guidelines.

In most states, electrical work on facilities used by employees or the general public must be done by a licensed electrician. The electrician takes the responsibility and liability for meeting the necessary codes.

Service Entrance

The electrical service must be of adequate size to handle the load (table 8-1). It provides a safe entrance and disconnect for the electric supply wires entering the building. It can also be used as the point where distribution and grounding take place.

To avoid multiple base charges, install one electrical service to serve all the greenhouses and accessory buildings. It is usually less expensive if a farm rate can be obtained rather than a commercial rate, although not all electric suppliers have this rate.

As more equipment is added, an electric service may become overloaded. If operated at 80% of its rating for more than three hours, overheating may occur with the possibility of wiring deterioration or fire.

In calculating load, it is necessary to make a complete list of electrical equipment, giving full-load amperes and operating voltage. Next, identify the equipment that will be operating simultaneously. This has a demand factor of 100%. The next 60 amps of all other loads is assigned a demand factor of 50%, with the remainder assigned at 25%. An additional amount, usually 25%, should be added for future expansion of the operation or for additional equipment.

TABLE 8-1. Sizing the electrical service

Greenhouse area	Electrical service (amps)	Entrance size [a] (volts)
<5,000 square feet	60	240
5,000–20,000	100	240
20,000–30,000	150	240
30,000–40,000	200	240
40,000–80,000	400	240
80,000–120,000	600	240
120,000–160,000	400	440
160,000–200,000	600	440
200,000–300,000	800	440

[a] Excluding plant lighting and motors greater than 5 horsepower.

The best location for the service entrance is in a dry, easily accessible area. The utility room of the headhouse is a good choice. In small operations, the service entrance may be placed on an endwall in one of the greenhouses. A waterproof box should be used.

Grounding

All electrical systems in farm operations must be properly grounded. Grounding helps to limit high voltages from lightning or a fault. It also limits the maximum voltage to ground from the hot wires. A number of grounding methods are used, including a metal underground water pipe system, the metal frame of a building (if it is grounded), or a copper rod driven 8 feet into moist soil.

Distribution Systems

Electricity is distributed from the service entrance through individual

MOTORS

Electric motors power a lot of greenhouse equipment. With minimum care, they will give many years of service.

Occasionally, motors have to be replaced. This may be caused by factors such as normal bearing wear, dust and dirt accumulating on heat-transfer surfaces, overloading from a machine that malfunctions, or low voltage in the electrical supply.

Determining Motor Failure

When a motor fails, the cause of failure should be determined. An overloaded motor runs hot and slow and draws more than the nameplate amperage. It will give off an odor of burning varnish or trip the thermal overload switch. Amperage draw can be determined with an ammeter and compared against the rating on the nameplate.

Overheating is frequently caused by low voltage at the motor. This can be from too small a wire size for the distance from the electric source or too many motors or electrical devices connected to one line. Use a volt meter to check the voltage at the motor when it is operating under load.

Since the power produced by a motor is the product of the voltage multiplied by the amperage (current), a low voltage causes an increase in the current required. The increase in heating effect is in direct proportion to the square of the increase in current. Doubling the current increases the heating effect fourfold.

You cannot tell by touch if a motor is running hot, as the normal operating surface temperature is generally 90˚–120˚F above the air temperature—enough to burn your hand.

Replacing a Motor

A defective motor should be replaced with one of the same horsepower rating and voltage. Today, consideration should be given to installing a high-efficiency model. These motors use more electrically conductive materials than comparable standard motors and convert more electrical energy input into mechanical, load-driving output. For example, a 1-horsepower, capacitor-start motor operating on 115 volts draws 13.6 amps, whereas a similar high-efficiency motor will draw only 9.2 amps, a 32% savings. High-efficiency motors cost slightly more than standard ones, but this cost is quickly recovered.

Proper Maintenance

For the best, most economical performance, some periodic maintenance is required. The following service operations should be performed at least once a year and more often if the motor operates under severe heat, cold, or dust conditions.

CAUTION: **Disconnect power to the motor before starting any maintenance.**

- Remove dust and dirt. Wipe dirt and grease from external sur faces. Using compressed air, blow out passages that are coated or plugged. Excessive dirt causes overheating and wear of moving parts.
- Check bearings for wear. Excessive side or end play may cause the motor to draw a higher than normal starting current or develop less torque. Replace worn bearings.
- Lubricate the motor. Follow the manufacturer's recommendations.
- Check wiring. Repair or replace worn or frayed wires.
- Clean switch contacts using an electrical contact cleaner and a brush.
- Check pulleys and belts. Replace belts that are worn. Adjust tension so that there is a $^{1}/_{2}$- to $^{3}/_{4}$-inch deflection halfway between the pulleys. Be sure that pulleys are secure and aligned on the shafts.

circuits to the point of use—motors, lights, heaters, and so forth. Each circuit is protected by a circuit breaker that opens the circuit when an overload or short circuit occurs. A ground fault circuit interrupter (GFCI) should be installed on receptacle circuits where portable tools may be connected. Due to the potential for nuisance tripping, it should not be installed on circuits that connect to fans or heating equipment. Each circuit and its associated wiring must be sized to be equal or greater than the electrical demand from the equipment on that circuit.

In large gutter-connected greenhouses or operations with many individual greenhouses, feeder circuits are installed to reduce the amount of wiring needed. For example, a 200-amp service panel may have several 60-amp feeder circuits connected to it, one in each hoophouse. A distribution panel with branch circuits is located at the end of each feeder circuit to serve the motors and lights in the greenhouse. Feeder circuit wire size and the circuit breaker must be adequate to handle this load.

Wiring

To meet the NEC, the wire type should have insulation to fit the application: wet, dry, high-temperature, or having oil present. In many locations in greenhouses, especially where moisture and dust are present, the code requires that the wiring be placed in conduit. Polyvinyl chloride (PVC) conduit is a good choice, as it is corrosion-resistant, watertight, and easy to install. It must be properly supported to avoid sag. The conduit can be sized large enough to contain all the wires needed to serve one area of the greenhouse. Watertight electrical boxes and receptacles should also be included in the system to keep out moisture and dust.

One problem common in greenhouse operations is using too small a wire for the size of the load. This is a frequent cause of fan and furnace motor overheating and failure. It also uses extra electricity that is converted to heat in the wire. Correct wire size can be determined from a wire size table such as tables 8-2, 8-3, and 8-4 (page 56).

TABLE 8-2. Sizes of copper wire for single-phase, 115–120-volt motors, and a 2% voltage drop

	Minimum wire size Wire in cable conduit or earth			Length of wire to motor, in feet													
				20	30	40	50	60	80	100	120	160	200	250	300	400	500
Load (amps)	Types R, T, TW	Types RH, RHW, THW	Bare or covered, overhead in air [a]	Wire size (AWG or MCM)[b] (Note: Compare the size shown below with the size shown in the column to the left and use the larger size.)													
5	12	12	10	12	12	12	12	12	12	12	12	10	10	8	8	6	6
6	12	12	10	12	12	12	12	12	12	12	12	10	8	8	8	6	4
7	12	12	10	12	12	12	12	12	12	12	10	10	8	8	6	6	4
9	12	12	10	12	12	12	12	12	12	10	10	8	8	6	6	4	4
10	12	12	10	12	12	12	12	12	10	10	8	8	6	6	4	4	3
12	12	12	10	12	12	12	12	12	10	8	8	6	6	4	4	3	2
14	12	12	10	12	12	12	12	10	10	8	8	6	6	4	4	3	2
16	12	12	10	12	12	12	10	10	8	8	6	6	4	4	3	2	1
18	12	12	10	12	12	12	10	10	8	8	6	6	4	4	3	2	1
20	12	12	10	12	12	10	10	8	8	6	6	4	4	3	2	1	0
25	10	10	10	12	10	10	8	8	6	6	4	4	3	2	1	0	00
30	10	10	10	12	10	8	8	8	6	4	4	3	2	1	1	00	000
35	8	8	10	12	10	8	8	6	6	4	4	3	2	1	0	00	000
40	8	8	10	10	8	8	6	6	4	4	3	2	1	0	00	000	0000
50	6	6	10	10	8	6	6	4	4	3	2	1	0	00	000	0000	250
60	4	6	8	8	8	6	4	4	3	2	2	0	00	000	000	250	300
70	4	4	8	8	6	6	4	4	3	2	1	0	00	000	0000	300	350

Note: Use 125% of motor nameplate current for single motors.

[a] The wire size in overhead spans must be at least #10 for spans up to 50 feet and #8 for longer spans.

[b] AWG is American Wire Gauge, and MCM is thousand circular mil.

Lighting

In greenhouse operations, lighting is used in work areas and for plant lighting. Energy savings can be obtained by selecting the best light source, the correct intensity, and a fixture placement that will give uniformity.

Light Sources

A knowledge of the construction, efficiency, and electrical characteristics of light sources is useful in making the best choice for a particular task (figure 8-1, page 57). In the past few years, several new light sources with increased efficiency have become available. There are significant differences in efficiency among the different types (table 8-5, page 57).

Incandescent

The standard bulb, first developed by Thomas Edison, is gradually being replaced by other types of bulbs. Incandescents are available in sizes from 10 to 500 watts and in 115 and 230 volts. Only about 10% of the input energy is converted to light. They should be used with a reflector to direct the light to the work area. Reflector and parabolic reflector bulbs have built-in reflectors.

Halogen

This is basically an incandescent lamp, but, because of the design and the halogen vapor, the light output remains constant throughout its life. Lamp life is about 2,000 hours for most sizes, which range up to 150 watts. Efficiency is relatively low compared to other types of lighting. Increased efficiency—up to 70% compared to incandescent—can be obtained with halogen infrared lamps.

Fluorescent

This is a linear light source providing more uniform illumination. The availability of several lengths, out-

TABLE 8-3. Sizes of copper wire for single-phase, 230–240-volt motors, and a 2% voltage drop

	Minimum wire size Wire in cable conduit or earth			Length of wire to motor, in feet													
				20	30	40	50	60	80	100	120	160	200	250	300	400	500
Load (amps)	Types R, T, TW	Types RH, RHW, THW	Bare or covered, overhead in air [a]	Wire size (AWG or MCM)[b] (Note: Compare the size shown below with the size shown in the column to the left and use the larger size.)													
2	12	12	10	12	12	12	12	12	12	12	12	12	12	12	12	12	12
3	12	12	10	12	12	12	12	12	12	12	12	12	12	12	12	12	10
4	12	12	10	12	12	12	12	12	12	12	12	12	12	12	12	10	10
5	12	12	10	12	12	12	12	12	12	12	12	12	12	12	10	10	8
6	12	12	10	12	12	12	12	12	12	12	12	12	12	10	10	8	8
8	12	12	10	12	12	12	12	12	12	12	12	12	10	10	8	8	6
10	12	12	10	12	12	12	12	12	12	12	12	10	10	8	8	6	6
12	12	12	10	12	12	12	12	12	12	12	12	10	8	8	8	6	4
14	12	12	10	12	12	12	12	12	12	12	10	10	8	8	6	6	4
17	12	12	10	12	12	12	12	12	12	10	10	8	8	6	6	4	4
20	12	12	10	12	12	12	12	12	10	10	8	8	6	6	4	4	3
25	10	10	10	12	12	12	12	10	10	8	8	6	6	4	4	3	2
30	10	10	10	12	12	12	10	10	8	8	8	6	4	4	4	2	1
35	8	8	10	12	12	12	10	10	8	8	6	6	4	4	3	2	1
40	8	8	10	12	12	10	10	8	8	6	6	4	4	3	2	1	0
45	6	8	10	12	12	10	10	8	8	6	6	4	4	3	2	1	0
50	6	6	10	12	10	10	8	8	6	6	4	4	3	2	1	0	00
60	4	6	8	12	10	8	8	8	6	4	4	3	2	1	1	00	000
70	4	4	8	12	10	8	8	6	6	4	4	3	2	1	0	00	000
80	2	4	6	10	8	8	6	6	4	4	3	2	1	0	00	000	0000
100	1	3	6	10	8	6	6	4	4	3	2	1	0	00	000	0000	250

Note: Use 125% of motor nameplate current for single motors.

[a]The wire size in overhead spans must be at least #10 for spans up to 50 feet and #8 for longer spans.

[b]AWG is American Wire Gauge, and MCM is thousand circular mil.

TABLE 8-4. Sizes of copper wire for three-phase, 230–240-volt motors, and a 2% voltage drop

	Minimum wire size Wire in cable conduit or earth			Length of wire to motor, in feet													
				20	30	40	50	60	80	100	120	160	200	250	300	400	500
Load (amps)	Types R, T, TW	Types RH, RHW, THW	Bare or covered, overhead in air [a]	Wire size (AWG or MCM)[b] (Note: Compare the size shown below with the size shown in the column to the left and use the larger size.)													
2	12	12	10	12	12	12	12	12	12	12	12	12	12	12	12	12	12
3	12	12	10	12	12	12	12	12	12	12	12	12	12	12	12	12	12
4	12	12	10	12	12	12	12	12	12	12	12	12	12	12	12	12	10
5	12	12	10	12	12	12	12	12	12	12	12	12	12	12	12	10	10
6	12	12	10	12	12	12	12	12	12	12	12	12	12	12	10	10	8
8	12	12	10	12	12	12	12	12	12	12	12	12	12	10	10	8	8
10	12	12	10	12	12	12	12	12	12	12	12	12	10	10	8	8	6
12	12	12	10	12	12	12	12	12	12	12	12	10	10	8	8	6	6
15	12	12	10	12	12	12	12	12	12	12	10	10	8	8	6	6	4
20	12	12	10	12	12	10	12	12	12	10	10	8	8	6	6	4	4
25	10	10	10	12	12	12	12	12	10	10	8	8	6	6	4	4	3
30	10	10	10	12	12	12	12	10	10	8	8	6	6	4	4	3	2
35	8	8	10	12	12	12	10	10	8	8	8	6	4	4	4	2	1
40	8	8	10	12	12	12	10	10	8	8	6	6	4	4	3	2	1
45	6	8	10	12	12	10	10	8	8	6	6	4	4	3	2	1	0
50	6	6	10	12	12	10	10	8	8	6	6	4	4	3	2	1	0
60	4	6	8	12	10	10	8	8	6	6	4	4	3	2	1	0	00
70	4	4	8	12	10	8	8	8	6	4	4	3	2	1	1	00	000
80	3	4	6	12	10	8	8	6	6	4	4	3	2	1	0	00	000
100	1	3	6	10	8	8	6	6	4	4	3	2	1	0	00	000	0000
120	0	1	4	10	8	6	6	4	4	3	2	1	0	00	000	0000	250
150	000	0	3	8	6	6	4	4	3	2	1	0	00	000	0000	250	300
180	0000	000	1	8	6	4	4	3	2	1	0	00	000	0000	250	300	400
210	250	0000	0	8	6	4	4	3	2	1	0	00	000	0000	250	350	500
240	300	250	00	6	4	4	3	2	1	0	00	000	0000	250	300	400	500

Note: Use 125% of motor nameplate current for single motors.

[a]The wire size in overhead spans must be at least #10 for spans up to 50 feet and #8 for longer spans.

[b]AWG is American Wire Gauge, and MCM is thousand circular mil.

puts, and spectral variations make them adaptable to many lighting tasks. Lamp life is 12,000 hours or more. Fluorescent lamps have a rather rapid decay rate and should be checked and replaced on a regular schedule. A ballast, which provides adequate voltage for starting the electric discharge and limits the current, is required. Compact fluorescent bulbs are a good choice to replace incandescent bulbs and save energy.

Metal Halide (MH) and High-Pressure Sodium (HPS)

These high-intensity discharge (HID) light sources produce light when an electric current passes through a gas or vapor under pressure. They have the highest efficiency of any commercially available bulb. Lamp fixtures include the required ballast and a reflector. Because of the high pressure required, it takes several minutes for the lamps to reach full brightness.

Reflectors

Reflectors should be designed to provide a uniform pattern over the work area. Computer programs are available to help with fixture placement for HID light sources. Some reflectors can be adjusted to keep light from spilling into areas that do not need it. They should be kept clean to increase light levels.

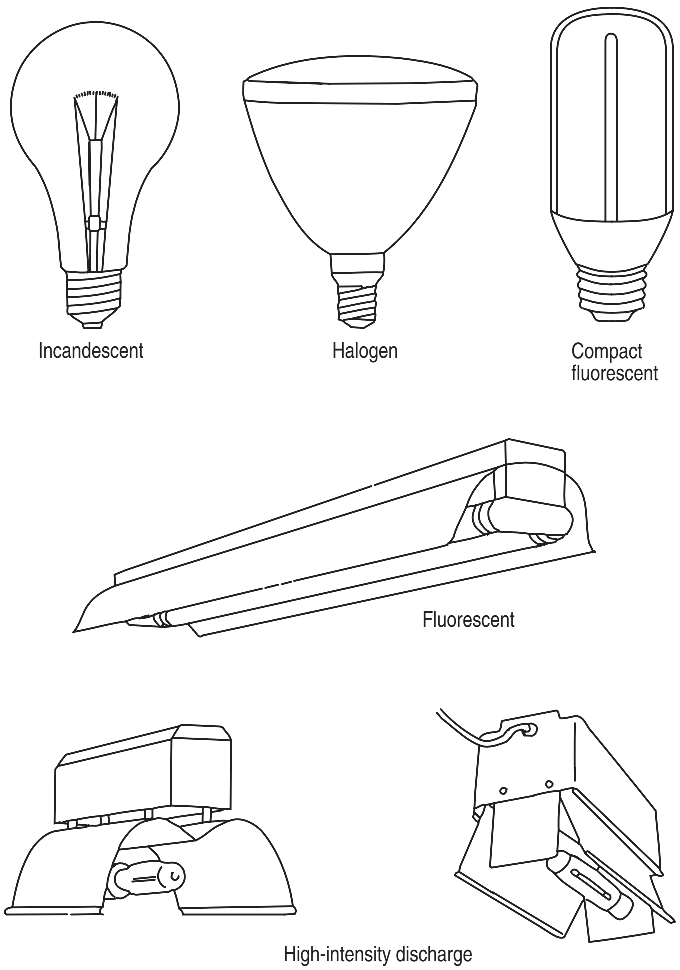


FIGURE 8-1. Types of lighting common for supplemental greenhouse illumination

Light Intensity

Fluorescent or metal halide lamps are the best for work areas. Install them at a level of 20–25 foot-candles at work surfaces for potting and transplanting and in office space and at 10 foot-candles in storage areas. Use an inexpensive light meter to measure the level or estimate the number of lumens and fixtures needed from the following formula:

Lamp lumens required = A x FC x LLF

Where,

A = Area to be lighted in square feet

FC = Light level in foot-candles

LLF = Light-loss factor (use 2 for reflective walls and ceiling, use 3 for dark walls and ceiling)

Note: See table 8-5 to convert lamp lumens to lamp watts.

Example: How many two-tube fluo-rescent fixtures are required to provide 20 foot-candles to a 600-square-foot transplanting area in a headhouse? The walls and floor are painted white (LLF=2). Each two-

TABLE 8-5. Comparison of light sources

Light source	Typical lamp wattage (watts)	Ballast wattage (watts)	Total wattage (watts)	Initial lumens (lumens)	Average life (hours)	Initial lumens/watt, including ballast (lumens/watt)
Incandescent	40		40	460	1,500	12
	100		100	1,620	1,000	16
	200		200	3,350	1,000	17
Halogen	75		75	1,000	2,000	14
	250		250	5,000	4,000	20
Fluorescent	40	7	47	3,000	7,500	64
Cool white (CW)	75	9	84	6,300	12,000	75
CW—high output	110	28	138	9,200	12,000	67
CW—very high output	215	47	262	15,500	9,000	59
Gro-lux	40	7	47	925	12,000	20
Wide spectrum	40	7	47	1,700	12,000	36
Metal halide	250	45	295	20,500	10,000	69
	400	55	455	34,000	20,000	75
	1,000	80	1,080	110,000	11,000	102
High-pressure sodium	250	50	300	27,500	24,000	92
	400	74	474	50,000	24,000	105
	1,000	145	1,145	140,000	24,000	122

Adapted from Aldrich and Bartok, Greenhouse Engineering, NRAES–33, 1994 and Both, "HID Lighting in Horticulture: A Short Review," In Greenhouse Systems: Automation, Culture, and Environment, NRAES–72, 1994.

tube fixture has an output of 6,000 lumens.

Lumens required = 600 x 20 x 2 = 24,000 lumens

$$\text{Number of fixtures} = \frac{24{,}000 \text{ lumens}}{6{,}000 \text{ lumens/fixture}}$$

= 4 two-tube fixtures

Fluorescent fixtures are standard for growth chambers. Levels of 1,000 foot-candles or more are needed to get good plant growth.

Growth rooms are frequently used to start plugs or root cuttings. Fluorescent or HID fixtures work well for this application. Reflectors designed for low mounting height are available. Light levels of 1,000–2,000 foot-candles are common. Provisions must be made to remove the excess heat from the lamps.

Supplemental light is frequently added in the greenhouse to compensate for cloudy weather or short day length (table 8-6). Metal halide and high-pressure sodium bulbs are the most efficient and create the least amount of shading. Some computer systems can integrate the daily sunlight with enough hours of artificial light. An average irradiance of 26 moles/square meter-day from the combination of sunlight and supplemental artificial light will effectively grow most species of higher plants. An installed light level of up to 1,500 foot-candles at plant height is practical to prevent too much heat buildup and shading from the fixtures.

USEFUL LIGHTING CONVERSION FACTORS

For light in general:
1 foot-candle = 1 lumen/square foot
1 foot-candle = 0.093 lux
1 foot-candle = 10.76 lumens/square meter
1 lumen/square meter = 1 lux

For PAR, photosynthetically active radiation (400–700 nanometers), from a cool white fluorescent lamp:
1 foot-candle = 0.031 Watt/square meter
1 foot-candle = 0.144 µmol/square meter-second
1 lux = 0.0029 Watt/square meter
1 lux = 0.0133 µmol/square meter-second

For PAR (400–700 nanometers) from a metal halide (MH) lamp:
1 foot-candle = 0.033 Watts/square meter
1 foot-candle = 0.153 µmol/square meter-second
1 lux = 0.0031 Watts/square meter
1 lux = 0.0143 µmol/square meter-second

For PAR (400–700 nm) from a high-pressure sodium (HPS) lamp:
1 foot-candle = 0.0263 Watts/square meter
1 foot-candle = 0.153 µmol/square meter-second
1 lux = 0.0025 Watts/square meter
1 lux = 0.0123 µmol/square meter-second

Adapted from: Both, A. J. 1994. "HID Lighting in Horticulture: A Short Review." In the proceedings *Greenhouse Systems: Automation, Culture, and Environment*. NRAES–72. Natural Resource, Agriculture, and Engineering Service (NRAES), Ithaca, New York.

Summary of the Relationship of Supplemental Lighting to Plant Light Requirements

For best growth, plants generally require about 26 mol/square meter-day…
= 300 µmol/square meter-second for 24 hours
= 600 µmol/square meter-second for 12 hours

300 µmol/square meter-second is approximately 2,100 foot-candles fluorescent light or 1,800 foot-candles of high-pressure sodium light.

Maximum sunlight = 2,000 µmol/square meter = 10,000 foot-candles

Water

Irrigation is one of the most critical operations in the production of plants. Watering systems are used every day, and conservation of both water and electricity can be achieved by selecting the best system for the crops that are grown.

Usage

Plants require an adequate supply of moisture for optimum growth and maximum production. For each pound of fresh matter produced by the plant, as much as 2–2.5 gallons of water move through the plant. With many irrigation systems to chose from, it is important to select one that will provide good growth without wasting water. Traditional overhead systems apply water in a circular pattern and irrigate both the

TABLE 8-6. Recommendations for supplemental greenhouse plant lighting

Plant species	Crop stage	Minimum lighting level µWatt/square meter	Minimum lighting level Foot-candles	Daylength hours
Alstroemeria	Cultivation	3,000	120	13
Antirrhinum	Propagation	9,000	340	16
	Cultivation	4,500	170	24
Azalea	Propagation	6,000	230	18
	Forcing	3,000	120	16
Bedding plants	Seedlings	6,000	230	16
Begonia	Stockplants/Propagation	6,000	230	14
Bromeliads	Propagation	6,000	230	18
	Forcing	4,500	170	24
Cacteae	Propagation	9,000	340	18
Calceolaria	Forcing	3,000	120	24
Camellia	Cultivation	4,500	170	14
Chrysanthemum	Stockplants	9,000	340	20
	Rooting	6,000	230	20
	Cut flowers	4,500	170	18
Cyclamen	Propagation	6,000	230	18
Ferns	Propagation	6,000	230	18
Foliage	Cuttings/Propagation	6,000	230	16
Geranium	Stockplants	7,000	270	16
	Cuttings	9,000	340	16
Gerbera	Stockplants/Propagation	6,000	230	16
Gesneria	Propagation	6,000	230	18
	Cultivation	4,500	170	18
Gladiolus	Cut flowers	8,000	730	16
Kalanchoe	Stockplants	6,000	230	18
	Rooting/Propagation	6,000	230	16
Nursery Stock	Rooting/Propagation	7,500	290	24
Orchids	Production	9,000	340	16
Roses	Cultivation	6,000	230	24
Sinningia (gloxinia)	Propagation	6,000	230	18
Stephanotis	Cultivation	4,500	170	18
Succulents	Seedlings	9,000	340	16
Vegetable crops				
Cucumber	Propagation	4,500	170	16
Lettuce	Seedlings (growth room)	25,000	950	24
	Crop production (greenhouse)	7,000	270	16
Strawberries	Fruit production	350	15	8
Tomatoes	Seedlings	6,000	230	16

Adapted from Application of Growlights in Greenhouses, PL Lightsystems, St. Catherines, Ontario and Phillips Lighting Application Guide, Philips Lighting Co., Somerset, NJ.

plants and the area in between. As much as 80% of the water may not reach the root system. This wastes water and can lead to groundwater contamination.

Trickle Systems

These systems place the water right where it is needed, near the root system. Moisture is supplied to the root zone through drip tubes or drip tape (figure 8-2, page 60). Water is dripped continuously or intermittently into the root zone around the plant. Soil between row crops or out of the plant area does not receive water. Although the water is applied to a small area around the plant, lateral transmission takes place throughout the soil media. Major advantages of trickle irrigation are that plant foliage remains dry and water application efficiency is high. Problems include clogging of the emitters and the drip tubes falling out of the pots.

Drip tubes are commonly used for potted-plant production, especially hanging baskets. The system consists of small-diameter plastic capillary tubes connected to a polyethylene supply pipe. Drop-in weights hold the tubes in the pots. In-line drippers are also available. These are manufactured as part of the supply pipe, and the pipe is placed on top of a row of pots or woven through bays of media for tomatoes or cucumbers.

Perforated tapes are designed for watering benches, beds, or capillary mats. Water oozes from seams, tiny holes, or emitters at a very low flow rate. Uniform distribution is achieved over long lengths by using engineered emitters.

Boom Irrigators

This equipment can be applied to existing greenhouses or new construction. The system consists of one or more pipes suspended from an overhead rail system or a cart that moves down an aisle. Water is supplied by a trailing hose, and the system is powered by a battery pack or electric supply cable. The boom unit can achieve much more even watering than hand watering or conventional overhead irrigation.

Although some growers have built their own systems, the most flexible systems use programmable controllers or microcomputers that allow speed changes, skipping of empty bench areas, selection of a boom section to activate, and multiple passes over the same area.

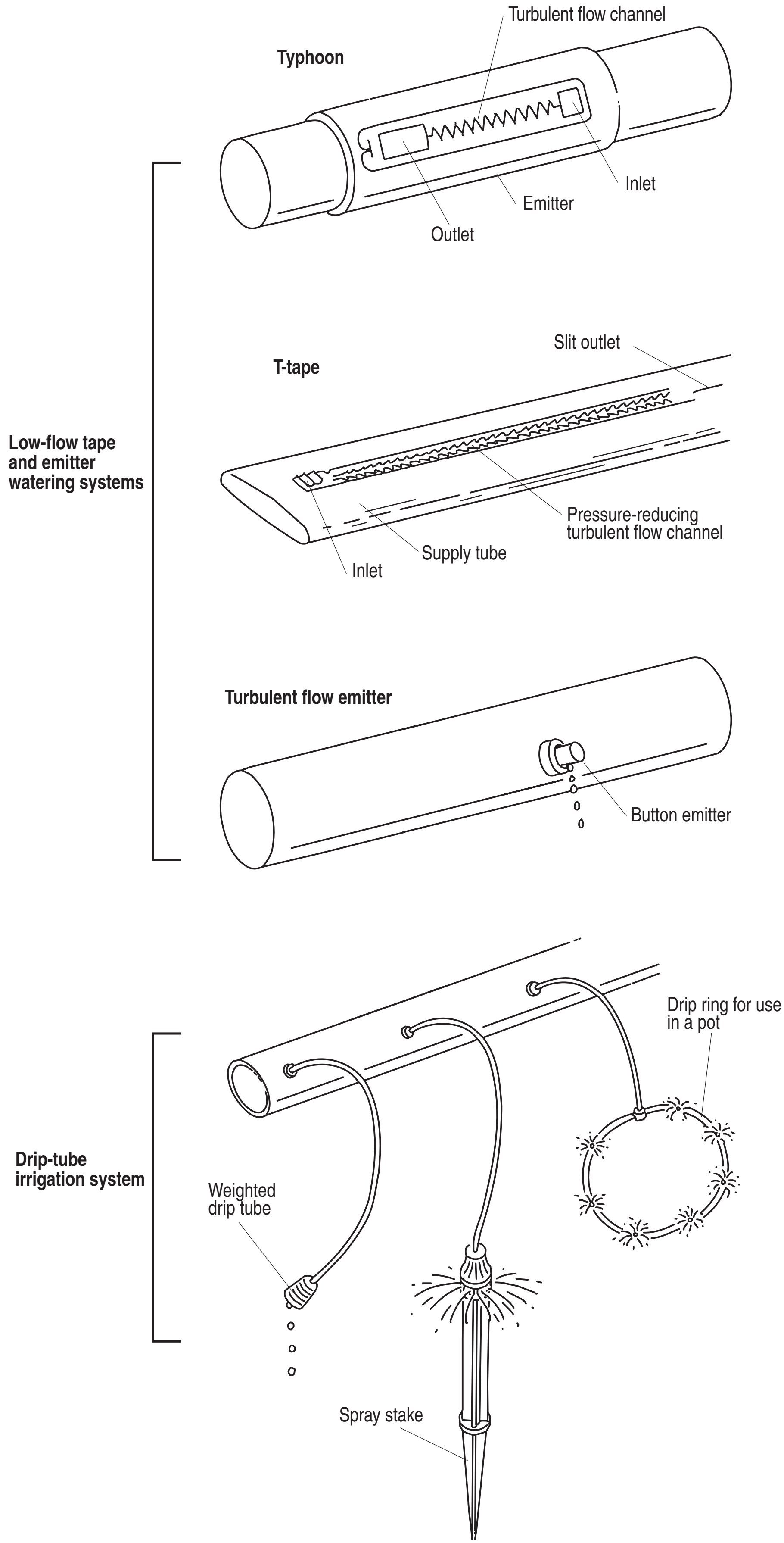


FIGURE 8-2. Trickle irrigation systems conserve water

In addition to greater uniformity of water application, which is especially important for plug production, less water is needed because the system can provide the optimum amount of water for the crop.

Ebb-and-Flood Irrigation

This system recycles excess water and nutrients, thereby preventing potential groundwater pollution. A tank, large enough to store all of the nutrient solution, contains a pump that supplies watertight benches, floor beds, or troughs.

A controller programs the length of time the water is available to the plants. Every plant gets the same amount of nutrient solution. There is a reduced incidence of disease, because the leaves remain dry. There is a potential for the spread of disease from the recycling of the water. The system is flexible, as it can be adapted to any size container. Energy is reduced, because less water is needed.

Equipment

Besides the drippers or nozzles, the watering system consists of a pump, pressure tank, piping, filter, and controls (figure 8-3). These need to be sized to fit the quantity of water needed to irrigate the crop.

Pumps

Match pump capacity to the maximum water-use rate or to the yield of the water supply. The total pressure against which a pump must work consists of four parts: (1) suction lift, or vertical distance water is lifted to the pump by suction; (2) vertical distance from the center line of the pump to the point where water is to be delivered; (3) required pressure at the outlet; and (4) friction in the piping system between the pump and nozzles.

Wiring

Adequate wiring is essential for continuous operation, energy efficiency, and safety. See tables 8-2, 8-3, and 8-4 (pages 54–56) for sizing the wire. Waterproof connection boxes should be used.

Pressure Tank

Most greenhouses connected to a private water system contain a pressure tank to store a quantity of water so that the pump doesn't have to start every time the faucet is turned on. This tank is located between the pump and point of water use, and pressure is developed by forcing water into the tank until air in the tank is compressed to a preset pressure. Most systems operate with the pressure switch set at 30–50 psi. Several sizes of tanks are available, from a 40-gallon to more than a 500-gallon capacity. The storage volume between the on and off setting is usu-

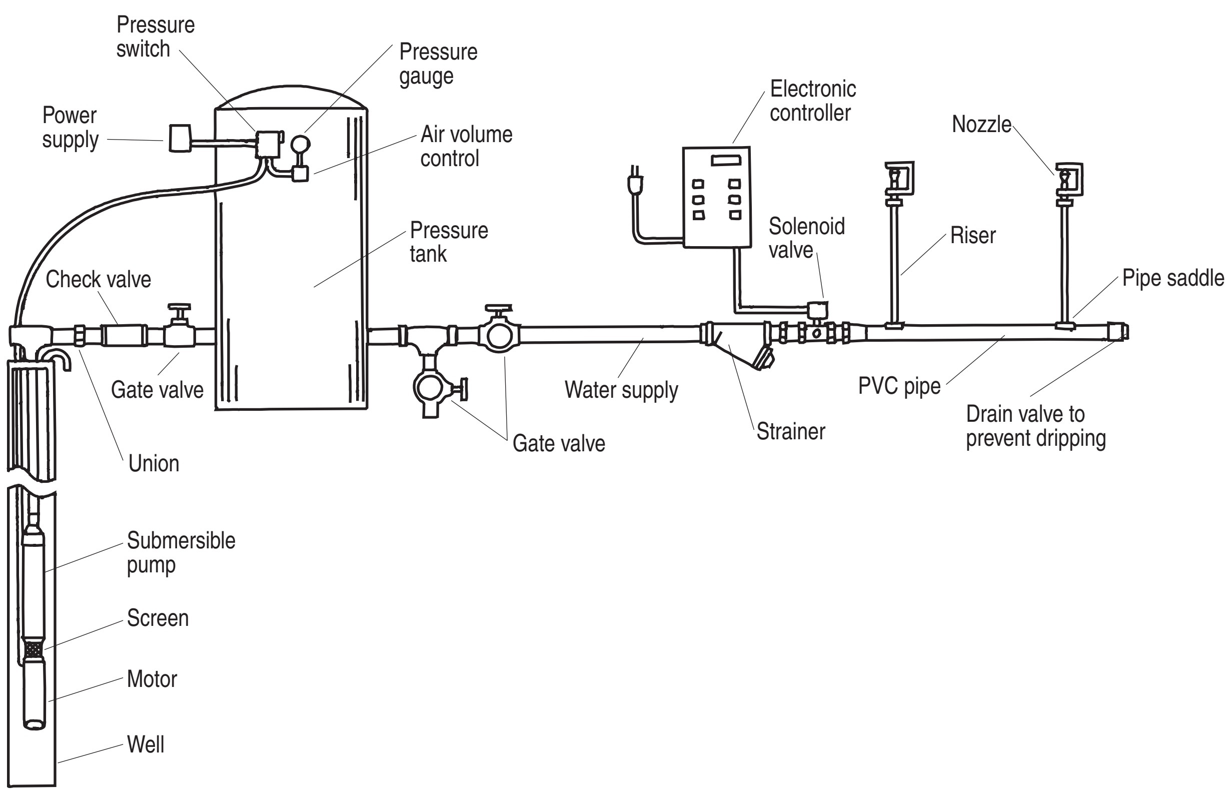


FIGURE 8-3. Automated irrigation system components

ally 20–40% of tank capacity. Usually a tank with ten times the pump capacity is installed (flow rate, gallons per minute x 10 minutes = gallons of tank capacity).

By storing water, the tank reduces the frequency of pump operation, reduces wear on the pump motor, and saves energy. If water replaces the air at the top of the tank(waterlogging), the pump will start frequently. To reduce waterlogging, the tank should be drained completely and then precharged with air to 15–20 psi pressure. This will double the gallons of water that will be drawn off between cycles.

Pipe Size

Polyethylene (PE) and polyvinyl chloride (PVC) pipe are most commonly used for supply and distribution lines. The cost is low, installation is easy, and the service life is good. Schedule 40 is common for $^{1}/_{2}$- and $^{3}/_{4}$-inch pipe sizes and schedule 80 for larger sizes or where a more rigid pipe is needed to reduce sag. Supply lines and laterals should be sized to carry the flow needed without excess friction loss. Friction loss is created when water flows through pipes, valves, fittings, and sprinklers or emitters. Because friction loss is cumulative between the source and the nozzles, allowances have to be made to ensure that each nozzle has an adequate pressure, or coverage will be uneven. For pressure loss tables, see tables 8-7 to 8-9 (pages 63–64) or consult a plumbing supply house. Backflow prevention is required if the system is connected to a municipal water supply or to a potable drinking water source.

Other Energy Conservation Measures

Water Heaters

Hot water is used for tempering plant irrigation water in the winter. A water temperature of about 90°F is commonly used for temperature-sensitive plants. Hot water could be supplied by a domestic or commercial hot water heater or by a loop and heat exchanger in the boiler. The tank should be large enough for the water needs of the crop. It should be insulated to conserve energy.

Domestic hot water temperatures for sinks and restroom facilities can be set at about 120°F to conserve energy. If the water heater has to be placed a long distance from the use point, an instantaneous water heater may be a better choice.

Hot Water Pipes

Pipes should be insulated to conserve energy. Use a minimum $^{1}/_{2}$-inch thickness. See table 5-6, page 31.

Drips

With the many fittings and connections in a greenhouse, drips are inevitable. A faucet dripping at 60 drops per minute will waste 113 gallons per month. If this is water heated with electricity at $0.11/kilowatt-hour, it will cost $3.50 per month.

TABLE 8-7. Friction loss in plastic pipe having standard I.D.

					Pounds/square inch (psi) per 100 feet of pipe				C=140	
Flow (gallons per minute)	**Pipe size (inches)**									**Flow (gallons per minute)**
	1/2	**3/4**	**1**	**1 1/4**	**1 1/2**	**2**	**2 1/2**	**3**	**4**	
1	0.49									1
2	1.80	0.45	0.14							2
3	3.70	0.95	0.30							3
4	6.40	1.60	0.50	0.13	0.07					4
5	**9.60**	2.50	0.75	0.20	0.10					5
6	13.40	3.40	1.10	0.28	0.13					6
7		4.60	1.40	0.37	0.17					7
8		5.80	1.80	0.48	0.23	0.07				8
9		**7.30**	2.20	0.59	0.28	0.08				9
10		8.80	2.70	0.72	0.34	0.10				10
11		10.50	3.30	0.85	0.41	0.12				11
12		12.40	3.80	1.00	0.48	0.14	0.06			12
13			4.40	1.20	0.55	0.16	0.07			13
14			**5.10**	1.30	0.63	0.19	0.08			14
15			5.80	1.50	0.72	0.22	0.09			15
16			6.50	1.70	0.81	0.24	0.10			16
17			7.30	1.90	0.91	0.27	0.11			17
18			8.10	2.10	1.00	0.30	0.12			18
19			9.00	2.40	1.10	0.33	0.13			19
20			9.80	2.60	1.20	0.36	0.15	0.06		20
22			11.80	3.10	1.50	0.44	0.18	0.07		22
24			13.80	**3.60**	1.80	0.52	0.22	0.08		24
25			14.90	3.90	1.90	0.56	0.23	0.08		25
26				4.30	2.00	0.59	0.25	0.09		26
28				4.80	2.30	0.68	0.29	0.10		28
30				5.50	2.60	0.77	0.32	0.11		30
35				7.30	**3.50**	1.00	0.43	0.15		35
40				9.30	4.40	1.30	0.54	1.90	0.06	40
45				11.60	5.50	1.60	0.70	0.24	0.07	45
50				14.10	6.60	2.00	0.83	0.29	0.08	50
60					9.30	**2.80**	1.20	0.40	0.11	60
70					12.40	3.70	1.60	0.54	0.15	70
80						4.70	**2.00**	0.69	0.19	80
90						5.90	2.50	0.86	0.23	90
100						7.10	3.00	1.00	0.28	100
120						10.00	4.20	**1.50**	0.39	120
140						13.30	5.60	1.90	0.52	140
160							7.20	2.50	0.66	160
180							8.90	3.10	0.83	180
200							10.80	3.80	**1.00**	200
220								4.50	1.20	220
240								5.30	1.40	240
260								6.10	1.60	260
280								7.00	1.90	280
300								8.00	2.10	300

Note: Values in green are at velocities over 5 feet/second and should be selected with caution.

C = Hazen-William coefficient of friction

TABLE 8-8. Friction loss in ordinary rubber hose

	Pounds/square inch (psi) per 100 feet of hose							
Flow (gallons per minute)	Hose size (inches)							Flow (gallons per minute)
	1/2	5/8	3/4	1	1 1/4	1 1/2	2	
0.5	0.40							0.5
1.5	3.02	1.01	0.42					1.5
2.5	7.75	2.58	1.08					2.5
5	27.80	9.37	3.86	0.95	0.32	0.13		5
10	99.50	33.20	13.80	3.38	1.14	0.47	0.12	10
15		71.00	29.60	7.25	2.45	1.01	0.25	15
20		121.00	50.30	12.40	4.15	1.71	0.42	20
25			76.50	18.70	6.34	2.60	0.64	25
30			108.00	26.50	8.96	3.68	0.90	30
35			142.00	34.80	11.80	4.83	1.18	35
40				44.70	15.10	6.20	1.52	40
45				55.00	18.60	7.65	1.87	45
50				67.50	22.80	9.35	2.28	50
60				94.30	31.80	13.10	3.19	60
70				126.00	42.50	17.50	4.25	70
80					54.60	22.50	5.48	80
90					67.50	27.80	6.80	90
100					81.50	33.50	8.19	100
125					124.00	50.60	12.40	125
150						72.10	17.60	150
175						94.50	23.10	175
200						122.00	29.60	200
225							36.80	225
250							44.60	250
275							53.30	275
300							62.50	300
325							72.50	325
350							83.20	350
375							94.50	375
400							107.00	400

TABLE 8-9. Quantity of water available from a city service line (for a 50-foot-long service line)

Size of service line (inches diameter)	Size of meter (inches)	Gallons per minute available (gpm)
3/4	5/8	10
3/4	3/4	12
1	3/4	18
1	1	22
1 1/4	1	30
1 1/2	1	35
1 1/2	1 1/2	45
2	1 1/2	60
2	2	75
3	3	160

Note: This information is intended only as a guide in determining the approximate water supply available. The information is based on a pressure drop of approximately 10 psi (pounds per square inch) from the city main through the service line and meter. For example, if the static pressure in the city main is 60 psi, then a 50-foot service line with a 1-inch diameter and a 3/4-inch meter should be capable of delivering 18 gallons per minute at 50 psi.

9 Trucking Costs

Getting plants to the right garden center at the right time at the right cost in good condition can be a challenge. With the increase in fuel prices, the cost of trucking has increased significantly. Now may be the time to review how your plants are handled and how the shipping process could be improved.

Many factors affect the cost of trucking. A survey by the American Trucking Association found that the skill and decisions made by the driver had the greatest impact. Other factors, in order of importance, include speed, equipment selection, tires, and idling.

Driver Training

The difference in fuel use between the best and worst drivers is about 35%, or about 3 cents per mile. A driver constantly makes decisions that affect fuel economy: when to shift, how fast to drive, how long to let the engine idle, when to brake, when and where to stop for fuel, which schedule to follow and route to take. Drivers that have gone through a formal training course usually do the best. These are available in most areas. The major trucking associations also have videos available to educate a new driver. Some companies award drivers for good performance.

Speed

Encourage drivers to slow down! Speed eats up fuel. Aerodynamics comes into play here. Moving a truck through the air faster creates more resistance and requires more energy. Increasing the speed from 55 to 65 miles per hour cuts fuel mileage by $^1/_2$–1 mile per gallon. Traveling at 75 miles per hour decreases it further. Many large trucking companies place governors on their trucks to maintain a maximum speed of 60–65 miles per hour. The lower speed also reduces tire, engine, and drive train maintenance. To offset the longer travel time, some companies share the savings with the driver.

Equipment Selection

There are many choices when selecting a truck—size, body style and material, engine horsepower, type of transmission, and accessory equipment. When possible, purchase a truck with lighter materials, such as aluminum or plastic versus steel. There is a fuel penalty of about 0.10 mile per gallon for each additional 100 pounds, and this is added wherever the truck travels. Carrying an unnecessary toolbox or extra cargo retainers increases the fuel penalty.

Sizing the truck is important. Do you purchase one that will handle the largest orders, or is it better to purchase a smaller truck and make two trips for the occasional large order? Should you have two sizes of trucks, one for local deliveries and one for long distance?

Consider body design. Narrow, curved hoods and bumpers reduce air resistance. Roof deflectors can increase miles per gallon up to 6% if they are designed properly and don't add too much extra weight.

It takes 18–20 horsepower to turn the cooling fan on a large rig. Installing an intermittent fan will save up to 5%. Also, the newer electronic-controlled diesel engines can save up to 14% over an older mechanical model.

Tires

Some long-distance haulers are reducing the size of the tires on their trucks and trailers. Going from 22.5- to 19.5-inch tires will reduce the weight about 400 pounds on a dual-tire axle. Low-profile or wide-base single tires are also an option. Selecting a rib tread design will save up to 14% over a rib and deep lug design.

Tire pressure and balance are also important. For every 10 pounds per square inch that a tire is below the ideal pressure, fuel mileage is reduced by 1%. Tire life is also reduced. Tire diameter is critical as well. Having tires with slightly different diameters on the same axle results in the smaller tire scuffing slightly on each revolution.

Idling

Idling costs the average over-the-highway truck operator $1,500 in fuel lost up the exhaust each year. A 400- to 500-horsepower diesel engine consumes about $^1/_2$ gallon per hour at idle speed. Some transportation companies program their electronically controlled engines to limit idling time to 7–10 minutes.

Fuel

With fuel prices escalating, where fuel is purchased makes a difference. Prices can be widely different between two cities and two stations. For greenhouse operations that deliver mostly locally, contracting or locking in a fuel price with a nearby distributor may save money.

How much fuel you carry also has an effect. At about 7.5 pounds per gallon, carrying an extra 50 gallons can reduce fuel mileage by 0.3 mile per gallon.

Scheduling

Growers in a panel discussion at a recent energy conservation meeting in Connecticut indicated that improved delivery scheduling is where major fuel savings can be realized. Delivering a few flats on demand or to correct a delivery mistake frequently costs more than the plants are worth. Making just-in-time deliveries to the large chains can also affect trucking costs. Picking up plant carts at the end of the season requires an extra trip to all the garden centers serviced. Scheduling software is available that will route trucks in the most efficient manner. It compares cost, mileage, and time.

Maintenance

Keeping an accurate log of daily miles traveled, out-of-route miles, fuel usage, and miles per gallon can help in pinpointing problems with scheduling and truck operation. A daily safety inspection should be part of the operator's routine. Scheduling preventive maintenance based on hours, days, or miles of operation will eliminate many breakdowns and lost time.

The high price of gasoline and diesel fuel is a good incentive to watch trucking costs. Proper selection of trucks, efficient routing, driver training, and a good maintenance schedule will help keep them under control.

10 Management

Management of the greenhouse—including management of crop selection, scheduling, the temperature regime, the use of prestarts or prefinished plants, supplemental lighting, and supplemental carbon dioxide—can influence the amount of energy consumed in many ways. Although each of these can help to reduce energy usage, there may be a penalty in dollars of income realized. In reviewing energy-conserving measures, one has to be balanced against the other. Although energy costs are high, they are only a small percentage of the total production cost.

Growing Cooler Crops

Some growers have changed their crop selection to grow a cooler-season crop during the winter. This requires having a market for the crop and the knowledge of how to grow it. Growing a crop that requires a 50°F rather than 60°F night temperature can save 25–30% on the fuel bill during December, January, and February in most northern climates. Tables 10-1 and 10-2 (page 68) list the minimum night temperatures for some of the common crops grown in greenhouses.

Shifting the Crop Schedule

Shifting the growing schedule to take advantage of higher light levels and longer days in the spring and fall can reduce heat requirements. For example, tomatoes can be grown as an early spring crop where the transplants are placed in the greenhouse in late January with fruit being first picked about April 1. They can also be grown as a late crop with the transplants being planted in mid-March and production starting about mid-May.

For growers selling wholesale to restaurants, the early crop usually works best, as the marketing season is longer. For the grower who sells through roadside stands, the later production may be better, as it complements bedding plant sales. The later planting requires about half the heat.

An alternative being used by an increasing number of growers is to install a growth room in the headhouse, garage, or basement to germinate seedlings in the early spring. By adding lights and increasing the shelf spacing, seedlings can be kept there an additional week or two. An installed light wattage of 25–30 watts per square foot of fluorescent light is needed. Research has shown that the growth rate of seedlings given optimum conditions continues for several weeks after the seedlings are transplanted and grown in the greenhouse. For smaller growers, a growth room delays starting up the greenhouse during the colder time of the year when heating costs are at their highest.

Another alternative is to build a small greenhouse just for propagation. It should have root zone heat and supplemental lighting to provide the optimum environment for the seedlings.

Using Plugs, Prestarts, or Prefinished Plants

Purchasing plugs can delay starting a greenhouse for a couple of weeks during the winter. You need to be able to get the varieties and quantities that fit your production schedule. Plug production is becoming a specialized segment of the greenhouse industry. Growers who produce plugs have greenhouses that

TABLE 10-1. Minimum recommended night temperature for selected floral crops

Minimum night temperature (˚F)	Crop	Minimum night temperature (˚F)	Crop	Minimum night temperature (˚F)	Crop
40	Anemone	55 (con't.)	Pelargonium	60 (con't.)	Senecio (forcing)
	Erica		Petunia		Tulipa (forcing)
	Ranunculus		Tropaeolum		Verbena
	Tulipa		Zantedeschia		Vinca
	Viola	60	Achimenes		Zebrina
45	Calceolaria		Alternanthera		Zinnia
	Calendula		Ardisia		Zygocactus
	Gypsophila		Asparagus	65	Aglaonema
	Primula		Astilbe (forcing)		Anthurium
50	Alstroemeria		Begonia		Araucaria
	Antirrhinum		Brassavola		Aspidistra
	Callistephus		Bromeliad		Browallia
	Citrus		Calceolaria		Cactus
	Cyclamen		Cattleya		Caladium
	Cymbidium		Chrysanthemum		Calanthe
	Dendrobium		Cissus		Capsicum
	Dianthus		Coleus		Codiaeum
	Freesia		Cosmos		Cordyline
	Heuchera		Crassula		Diffenbachia
	Lathyrus		Dahlia		Dracaena
	Lupinus		Euphorbia		Eucharis
	Myosotis		Ficus		Ferns
	Odontoglossum		Gardenia		Fittonia
	Paeonia		Grevillea		Hyacinthus (forcing)
	Schizanthus		Hedera		Impatiens
	Streptocarpus		Hippeastrum		Lantana
55	Celosia		Hoya		Maranta
	Centaurea		Hydrangea (forcing)		Pandanus
	Cypripedium		Kalanchoe		Peperomia
	Delphinium		Laelia		Phalaenopsis
	Exacum		Lilium (forcing)		Philodendron
	Fuchsia		Matthiola (growing, forcing)		Saintpaulia
	Gerbera		Narcissus (forcing)		Sansevieria
	Hyacinthus		Oncidium		Sinningia
	Iris (forcing)		Phlox		Strelitzia
	Miltonia		Rhododendron (forcing)		Vanda
	Muscaria (forcing)		Rosa		
	Paphiopedilum		Salvia		

Adapted from Poole and Badger, Management Practices to Conserve Energy in Ohio Greenhouses, OARDC Special Circular 104, 1980.

TABLE 10-2. Minimum recommended night temperature for selected vegetable crops

Minimum night temperature (˚F)	Crop	Minimum night temperature (˚F)	Crop	Minimum night temperature (˚F)	Crop
40	Chives	45 (con't.)	Carrot	45 (con't.)	Spinach
	Onion		Cauliflower	50	New Zealand spinach
	Salsify		Chard		Squash
	Shallot		Endive	60	Cucumber
45	Beet		Horseradish		Muskmelon
	Broccoli		Lettuce	65	Eggplant
	Brussels sprouts		Parsley		Pepper
	Cabbage		Radish		Tomato

Adapted from Lorenz and Maynard, *Knott's Handbook for Vegetable Growers,* Wiley-Interscience, 1980.

can provide optimum environmental control.

Prestarts are a more recent addition to the market. They delay the need to start greenhouses until even later into the season. Flats of preplanted seedlings are delivered on carts that are rolled into the greenhouse. The flats are then placed in the growing space.

You can order the variety of plants in the types of containers you need. There is usually a minimum order of 1,000 flats and a minimum of 25–50 flats of one variety. Another advantage to prestarts is that they can fill empty growing space immediately, thus increasing the number of crops that can be grown in the greenhouse during the busy spring season.

Many potted plants can be purchased prefinished. The propagator usually has space to grow the plants pot-to-pot, but the last few weeks or months as the foliage expands, the area required increases by several fold.

Prefinished plants offer the grower the opportunity to purchase plants in the quantity and quality to meet the customers' needs without expanding the facilities. They can also keep growing space in the greenhouse full. Some prefinished plants are grown in a southern climate, where energy costs are lower, and then shipped to northern growers when temperatures are warming up in the spring.

Keeping Growing Space Full

Space within the greenhouse has to be heated during the winter, so growing space should remain as full as possible to spread the cost of heat. Spacing potted plants as they grow may yield considerable savings. However, the cost of labor to move the plants has to be balanced against the cost of additional fuel needed to heat the space if plants were set at the final spacing.

Equipment is available to mechanically space plants. Spacing forks that fit onto a skid steer loader work well to space plants grown on the floor, such as with an ebb-and-flood system. For tray systems, automatic spacing equipment will take pots from one tray at one spacing and place them into a second tray at a wider spacing.

Adding Carbon Dioxide

Supplemental carbon dioxide can increase growth in many plants. Ambient air contains about 360 parts per million (ppm) of carbon dioxide. On a sunny day in a closed greenhouse, this level can drop to below 100 ppm. Levels up to 1,500 ppm can be utilized by plants such as lettuce, tomatoes, cucumbers, roses, chrysanthemums, and carnations.

To avoid wasting the added carbon dioxide, it must be added where there is sufficient light available for photosynthesis and when the greenhouse temperature is low enough to prevent the ventilation system from turning on.

Carbon dioxide can be added from a natural gas or propane burner, special equipment added to a gas-fired boiler, or pressurized tanks of the gas (figure 10-1, page 70). Sensors are available to monitor and control the desired concentration.

Closing the Greenhouse for Part of the Winter

Closing the greenhouse for part of the winter is common practice with bedding plant growers who grow in hoophouses heated with hot-air furnaces. A significant savings in fuel usage will result in northern greenhouses if they are not opened up until March. One-third of the heating season is during January and February. The greenhouses should be opened up and started only as the need for space expands during the spring season.

Before shutting down a greenhouse, consider the following:

- Heat may have to be provided during heavy snow to prevent the structure from collapsing. Snow may have to be removed from between adjacent greenhouses. Your insurance may be voided if the greenhouses are unheated.
- Water systems and boilers will have to be drained to prevent frozen pipes.
- For crops grown in or on the ground, it may take several days to bring the soil temperature up to acceptable levels once the greenhouse is started.
- What effect will the loss of production and income have on your business?

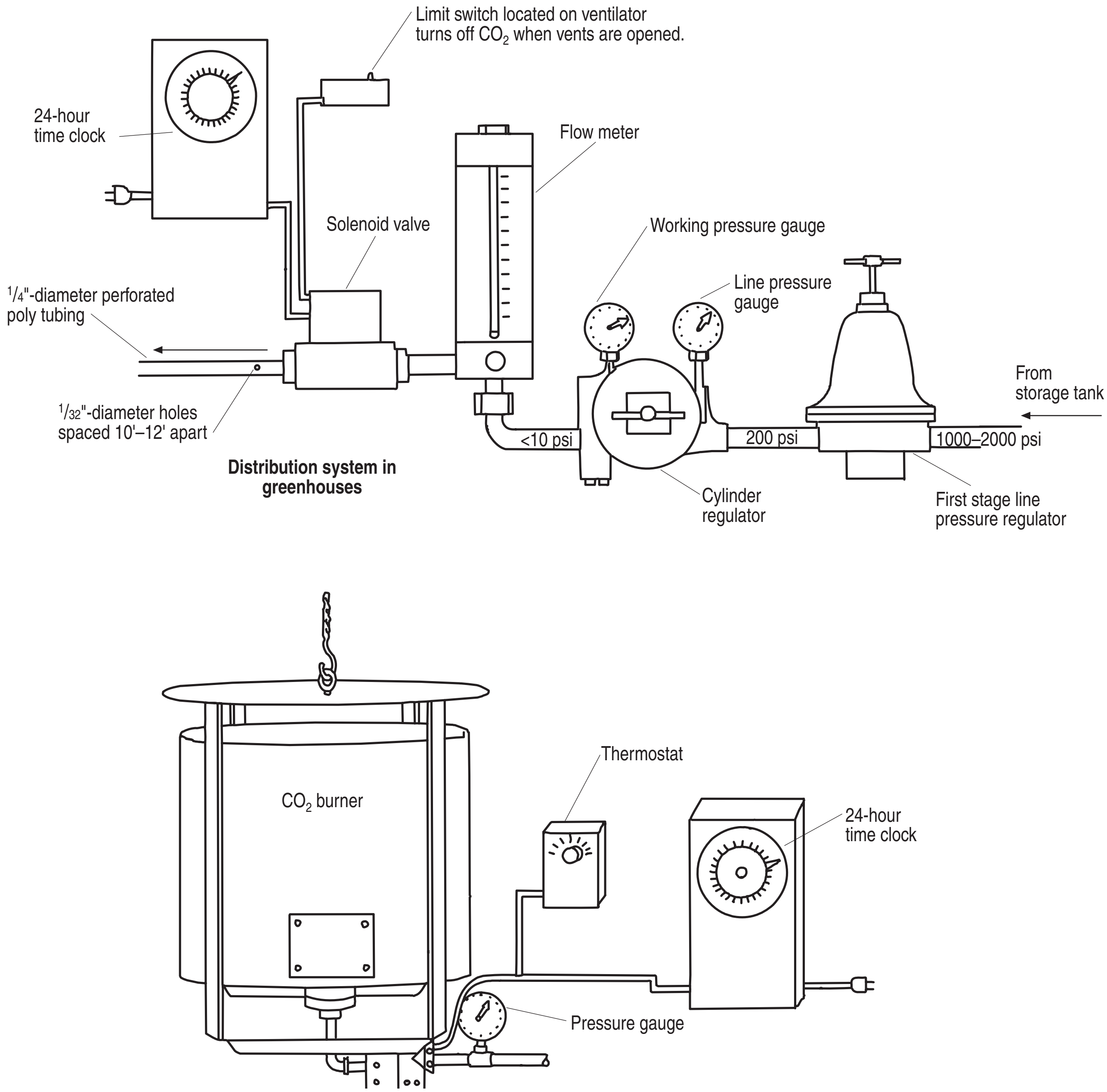


FIGURE 10-1. Equipment for adding carbon dioxide to the greenhouse

A Energy Conservation Checklist

Conserving Heating Energy

Providing heat in the greenhouse during the winter months consumes a large quantity of fuel oil or gas. There are many ways to reduce heat loss or increase heating system efficiency to reduce this consumption and reduce fuel costs. Below are some ways to realize savings through heat conservation.

Air Leak Reduction

- ✔ Keep doors closed; use door closer or springs.
- ✔ Weatherstrip doors, vents, and fan openings.
- ✔ Lubricate and adjust louvers frequently so that they close tightly. A partially open louver may allow several air changes per hour. Additional fuel is needed to heat this air. Shut off power to some fans during the winter, and cover openings with insulation or plastic to reduce air infiltration.
- ✔ Repair broken glass or holes in the plastic covering.

Coverings

- ✔ Line inside sidewalls and endwalls of the greenhouse with poly to increase the insulation effect. Install double-wall polycarbonate structured sheets on endwalls to get an insulation effect and save labor needed for recovering.
- ✔ Use double poly with air inflation.
- ✔ Add a single or double layer of plastic over glasshouses, and inflate it to get a double covering.
- ✔ Remove shade cloth or shade compound to increase light levels and heat gain.

Energy-Conserving Blankets

- ✔ Both manual and motorized systems are available.
- ✔ Tight closures should be maintained where curtains meet sidewalls, framing, or gutters.
- ✔ Use a U-shaped heat trap to prevent heat from escaping overhead (see figure 4-9, page 19). Heat and water lines should be insulated or located below the blanket.

Foundation and Sidewall Insulation

- ✔ When building new greenhouses, place 1–2 inches of polyurethane or polystyrene board to 24 inches deep to reduce perimeter heat loss.
- ✔ Use 1–2 inches of insulation board against concrete kneewalls. Insulating a 3-foot-high kneewall on a 28-foot-by-100-foot greenhouse with 2 inches of foam insulation will save about 400 gallons of fuel oil per year.
- ✔ Use aluminum-faced building paper or insulation board behind sidewall heat pipes or fin radiators to reduce heat loss, but leave air space next to the wall to prevent frost damage to the wall.

Site Location

- ✔ Locate new greenhouses in sheltered areas to reduce wind-induced heat loss (if this does not reduce light).
- ✔ Use a windbreak on the prevailing winter wind direction sides of the greenhouse. A windbreak can be a conifer tree belt or a plastic snow fence.

Efficient Heating Equipment

- ✔ Check boiler, burner, and backup systems to make sure they are operating at peak efficiency. Have furnaces cleaned and adjusted and an efficiency test run at least once a year. A 2% increase in efficiency for a 30-foot-by-150-foot greenhouse will save about 200 gallons of fuel oil.
- ✔ Clean heating pipes and other radiation surfaces frequently.
- ✔ Use electronic thermostats or controllers with a 1°F differential.
- ✔ Aspirate thermostats or sensors for more accurate temperature control.
- ✔ Use horizontal air flow (HAF) to get better temperature uniformity.
- ✔ Insulate distribution pipes in areas where heat is not required.
- ✔ Insulate the boiler itself if it isn't heating a work area.
- ✔ Check and repair leaks in valves, steam traps, and pipe.

Conserving Electricity

Many uses of electricity either reduce the labor needed or increase the productivity of the labor force. Electricity also has the advantage of being a willing and available worker at all times. This section will review ways to make electric usage more economic.

Wiring System

- ✔ Have the wiring system inspected by a competent electrician for overloading, corroded parts, or faulty insulation.
- ✔ Losses of electrical energy to heating of the wires can be reduced by using larger wire sizes.

Motors

- ✔ Motor size and type should be selected to meet the requirements of the equipment it is to operate.
- ✔ Replace motors with high-efficiency motors that reduce electric consumption by 2–5%.
- ✔ Keep proper belt tension and alignment.
- ✔ Use larger diameter fans with smaller motors. For example, a 36-inch fan with a $^1/_3$-horsepower motor will give the same output as a 30-inch fan with a $^1/_2$-horsepower motor with a savings in electricity cost of $3.00 per month. Both have an output of 7,800 cubic feet per minute.
- ✔ A power company voltage reduction of up to 8% will not affect most motors if the line supplying the motor is of adequate size and is not overloaded. A combined voltage drop due to power company reductions and load losses of more than 10% can cause motor overheating and damage. Use motors with thermal overload protection.

Lighting

- ✔ Keep light bulbs and fixtures clean. Use the correct size light bulb for the job.
- ✔ Replace incandescent bulbs with low-wattage, compact fluorescent bulbs at a savings of about two-thirds the electricity.
- ✔ Turn lights off when not needed.
- ✔ Install motion detectors to control security lights so they are not on all the time. Do not use HID (high-intensity discharge) lighting for this application, as the lighting time is several minutes.

Conserving Water

A large supply of water is needed to operate a greenhouse. The cost of this, whether it be in the form of a monthly water bill or operation charge of an individual water system, adds to the production cost of the plants. Water and the energy to move it can be conserved in several ways.

Pumps

- ✔ Service pumps at least twice each year.
- ✔ Provide adequate wire size for the pump motor to reduce heat loss from the wire and to provide sufficient voltage.

Tanks

- ✔ Use a larger pressure tank to eliminate frequent starting of the pump.
- ✔ Drain tanks when needed to avoid a "waterlogged" condition.
- ✔ Locate hot water tanks as close as possible to the most frequent use.
- ✔ Heat water to the lowest temperature that is needed for the job. Most hot water heaters should be set at 120°F.

Pipes

- ✔ Use a pipe size large enough to supply necessary water at minimum friction loss.

- ✔ Insulate hot water pipes to reduce heat loss.
- ✔ Eliminate all water leaks. A faucet dripping at 60 drops per minute will waste 113 gallons per month. If this is hot water and electricity costs $0.11 per kilowatt-hour, it will cost about $3.50 to heat it.

Managing and Maintaining Trucks, Tractors, and Equipment

- ✔ Regularly scheduled tune-ups can save 10% on fuel usage.
- ✔ Keep tires properly inflated. Use radial rather than bias-ply tires.
- ✔ Avoid lengthy idling. Idling can consume 15–20% of the fuel used.
- ✔ Run equipment in the proper gear for the load.

Managing for Efficiency

- ✔ Annual fuel consumption can be decreased approximately 3% for each 1°F reduction in night temperature. Use HAF (horizontal air flow) to maintain good air circulation and uniform temperature.
- ✔ Delay starting the greenhouse by a week or more. Build a germination/growth chamber to start seedlings.
- ✔ Root zone temperature is usually more critical than air temperature. Air temperature can be 5°–10°F lower than root zone temperature. Install root zone heating in the floor or under benches.
- ✔ Keep growing areas full at all times. Install movable benches to achieve 90% space utilization. Grow hanging baskets to get more production per greenhouse.

B Heat Loss Calculations

Step 1: List greenhouse dimensions in feet (see figure B-1).

Wall height, A =

House width, B =

House length, C =

Rafter length, D =

Lower-wall height, E =

Upper-wall height, F =

Gable height, G or H =

Step 2: Calculate the appropriate surface areas and perimeter.

N is the number of individual house sections forming each greenhouse range. N = 1 for a single house.

Lower-wall area: 2N(E x B) + (E x 2C) =

Upper-wall area: 2N(F x B) + (F x 2C) =

Single-material wall:
2N(A x B) + (A x 2C) =

Gable-roof area: 2N x D x C =

Curved-roof area: N x D x C =

Gothic-end area: W = 1.3N x B x H =

Curved-end area: X = 1.5N x B x H =

Gable area: Y = N x B x G =

Gable-roof area: Z = 1.1N x B x H =

Perimeter: 2[(N x B) + C] =

Definition of other terminology:

N = Number of individual greenhouses or greenhouse sections in a gutter-connected range.

U = Heat-transfer coefficient (Btu/hour-square feet-°F)

ΔT = Air temperature difference between inside and outside (°F)

Q_C = Heat loss by conduction (Btu/hour)

Q_A = Heat loss by air infiltration (Btu/hour)

Q_T = Total heat loss (Btu/hour)

Step 3: List construction materials for each surface and U values from table 1-2, page 7.

Lower wall: U_1 =

Upper wall: U_2 =

Single-material wall: U_3 =

End area: U_4 =

Roof: U_5 =

Perimeter: U_6 =

Step 4: Calculate appropriate conduction heat loss, Q_C.

$Q_C = U \times \text{Area} \times \Delta T$

ΔT = Inside night temperature – Minimum design temperature

(For minimum design temperature, see figure B-2 at right.)

Lower-wall area x U_1 x ΔT =

Upper-wall area x U_2 x ΔT =

Single-material wall area x U_3 x ΔT =

Gable- or curved-end area x U_4 x ΔT =

Roof area x U_5 x ΔT =

Perimeter length x U_6 x ΔT =

Total = Q_C =

Step 5: Calculate greenhouse volume.

Gable-roof house volume:
V = N[(A x B x C) + (B x G x C/2)] =

Single curved-roof house volume:
V = 2H x B x C/3 =

Multiple curved-roof volume:
V = N[(A x B x C) + (2H x B x C/3)] =

Step 6: Calculate air infiltration losses, Q_A.

$Q_A = 0.02 \times V \times \text{Air changes/hour} \times \Delta T$

Air changes per hour can be found in table 1-3, page 7.

Step 7. Calculate total heat loss, Q_T.

$Q_T = Q_C + Q_A$ =

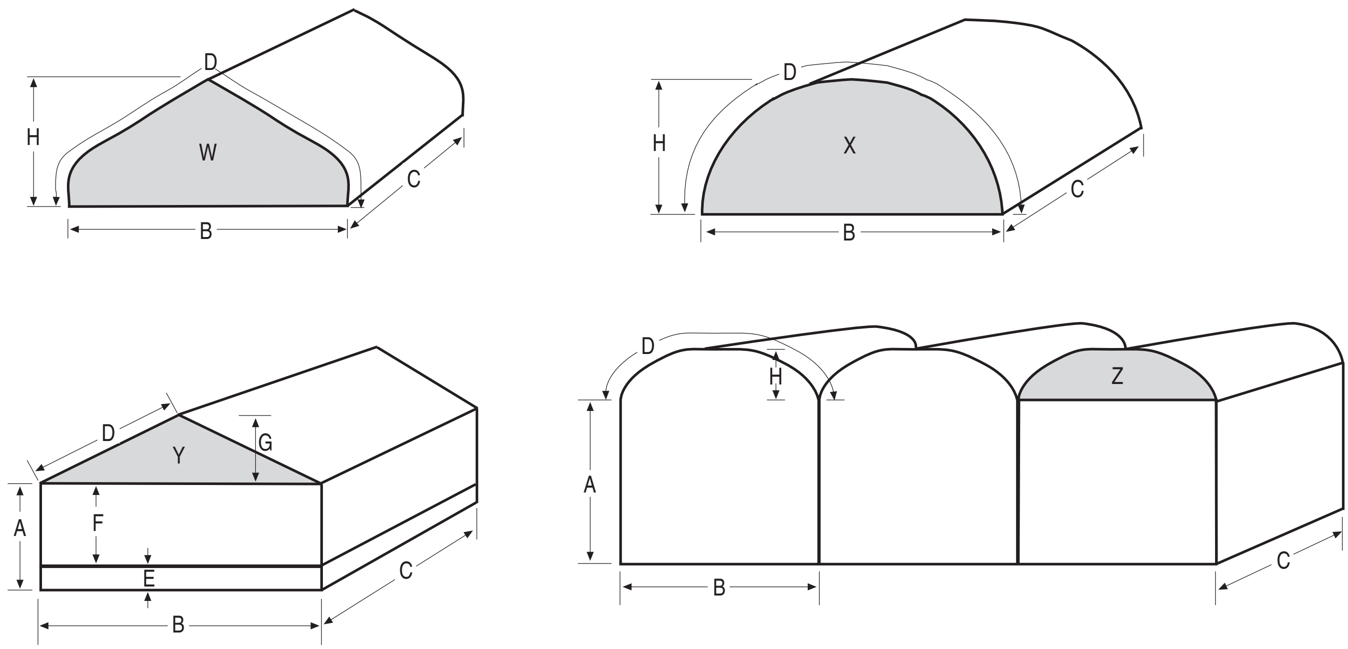


FIGURE B-1. Dimensions of various greenhouse shapes needed to calculate heat loss

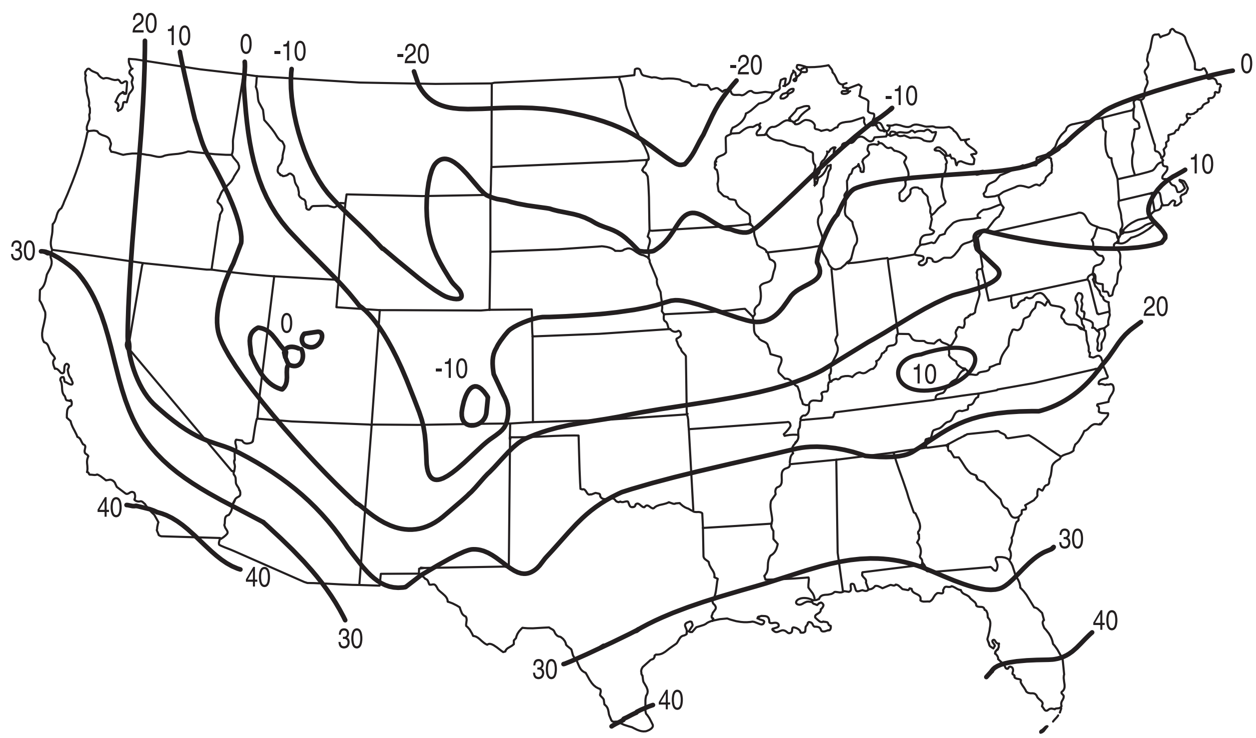
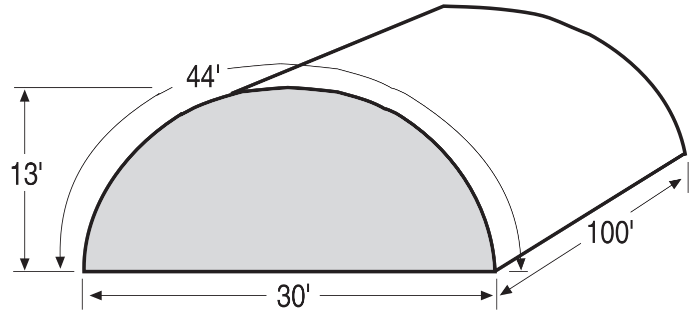


FIGURE B-2. Minimum greenhouse design temperatures across the United States

Sample Heat Loss Calculation

To size the heating system, calculate the expected heat loss from a new hoophouse covered by a double layer of poly. The foundation is insulated to a depth of 2 feet with polystyrene insulation board.

- Minimum desired inside temperature: 60˚F
- Minimum design temperature: 0˚F (see figure B-2, page 75)



Step 1. List greenhouse dimensions in feet.

Wall height, A = n/a

House width, B = **30 feet**

House length, C = **100 feet**

Rafter length, D = **44 feet**

Lower-wall height, E = n/a

Upper-wall height, F = n/a

Gable height, G or H = **13 feet**

Step 2. Calculate the appropriate surface areas and perimeter.

N is the number of individual house sections forming each greenhouse range. N = 1 for a single house.

Lower-wall area: n/a

Upper-wall area: n/a

Single-material wall area: n/a

Gable area: n/a

Curved-end area: 1.5N x B x H = **1.5 x 1 x 30 feet x 13 feet = 585 square feet**

Gable-roof area: n/a

Curved-roof area: N x D x C = **1 x 44 feet x 100 feet = 4,400 square feet**

Perimeter: 2[(N x B) + C] = **2[(1 x 30 feet) + 100 feet] = 260 linear feet**

Step 3. List construction materials for each surface and U factors from table 1-2, page 7.

Location, Construction Material, U Factor

Lower wall: U_1 = n/a

Upper wall: U_2 = n/a

Single-material wall: U_3 = n/a

End area: **Polycarbonate structured sheet, U_4 = 0.6**

Roof: **Double poly, U_5 = 0.7**

Perimeter: **Insulated, U_6 = 0.4**

Step 4. Calculate appropriate conduction heat loss, Q_C.

Q_C= Area x U x ΔT

ΔT= Inside night temperature – Minimum design temperature =

= 60˚F – 0˚F = 60 ˚F

Lower-wall area x U_1 x ΔT = n/a

Upper-wall area x U_2 x ΔT = n/a

Single-material wall area x U_3 x ΔT = n/a

Gable- or curved-end area x U_4 x ΔT =
585 x 0.6 x 60 = 21,060

Roof area x U_5 x ΔT =
4,400 x 0.7 x 60 = 184,800

Perimeter length x U_6 x ΔT =
260 x 0.4 x 60 = 6,240

Total = Q_C = **21,060 + 184,800 + 6,240 = 212,100 Btu/hour**

Step 5. Calculate greenhouse volume.

Gable-roof house volume: n/a

Single curved-roof house volume:
2H x B x C/3 =
2 x 13 feet x 30 feet x 100 feet/3 = 25,974 cubic feet

Multiple curved-roof volume: n/a

Step 6. Calculate air infiltration losses, Q_A.

Q_A = 0.02 x ΔT x V x Air changes/hour =
0.02 x 60 x 25,974 x 0.5 = 15,585 Btu/hour

(See table 1-3, page 7, for air changes per hour.)

Step 7. Calculate total heat loss, Q_T.

$Q_T = Q_C + Q_A$ =
212,100 + 15,585 = 227,685 Btu/hour

Note: If the greenhouse is located in a windy location, add an extra 10%. The total heat loss value (Q_T) is the amount of heat that is needed by the greenhouse on the coldest night. The boiler or furnace should have an output equal to this value. Most furnaces are rated by input heat value (the amount of fuel burned). This value has to be multiplied by the efficiency of the unit to get heat output. Most boilers and furnaces operate in the 70–80% efficiency range.

C Selected Product Manufacturers and Distributors

Combustion Test Kits

Bacharach, Inc.
625 Alpha Drive
Pittsburgh, PA 15238
Phone: (800) 736-4666
WWW.BACHARACH-INC.COM

Dwyer Instruments, Inc.
PO Box 373, 102 Highway 212
Michigan City, IN 46361
Phone: (219) 879-8000
WWW.DWYER-INST.COM

Grainger, Inc.
Phone: (888) 361-8649
WWW.GRAINGER.COM

Lynn Products Company, Inc.
400 Boston Street
Lynn, MA 01905
Phone: (781) 593-2500
WWW.LYNNPRODUCTS.COM

Controllers and Computer Systems

Acme Engineering & Manufacturing Corporation
PO Box 978
Muskogee, OK 74402
Phone: (918) 682-7791
WWW.ACMEHORT.COM

Aerotech, Inc.
4215 Legion Drive
Mason, MI 48854-1036
Phone: (517) 676-7070
WWW.AEROTECH-INC.COM

Agra Tech, Inc.
2131 Piedmont Way
Pittsburg, CA 94565
Phone: (925) 432-3399
WWW.AGRA-TECH.COM

Argus Control Systems Ltd.
1281 Johnston Road
White Rock BC V4B 3Y9
Canada
Phone: (604) 538-3531
WWW.ARGUSCONTROLS.COM

Micro Grow Greenhouse Systems, Inc.
26111 Ynez Road #C4
Temecula, CA 92591
Phone: (909) 296-3340
WWW.MICROGROW.COM

Priva Computers, Inc.
3468 South Service Road
Vineland ON L0R 2E0
Canada
Phone: (905) 562-7351
WWW.PRIVA.CA

Q-Com Corporation
2154 Michelson Drive, Suite A
Irvine, CA 92612
Phone: (949) 833-1000
WWW.QCOMCORP.COM

Wadsworth Control Systems
5541 Marshall Street
Arvada, CO 80002
Phone: (303) 424-4461
WWW.WADSWORTHCONTROLS.COM

Energy Blankets and Shade Systems

Cravo Equipment Ltd.
White Swan Road RR#1
Brantford ON N3T 5L4
Canada
Phone: (519) 759-8226
WWW.CRAVO.COM

Gintec Shade Technologies, Inc.
RR#1
Windham Centre ON N0E 2A0
Canada
Phone: (519) 443-4743
WWW.GINTEC-SHADE.COM

Green-Tek, Inc.
407 North Main Street
Edgerton, WI 53534
Phone: (608) 884-9454
WWW.GREEN-TEK.COM

LS Svensson
1813 Associates Lane, Suite E
Charlotte, NC 28217
Phone: (800) 742-3391
WWW.LSAMERICAS.COM

VRE Systems
RR#1 7367 Young Street
Grassie ON L0R 1M0 Canada
Phone: (905) 945-8863
WWW.VRESYSTEMS.COM

Heating Systems

A.I.M. Radiant Heating Supplies
6591 Route 23
Acra, NY 12405
Phone: (518) 662-3160

Delta T Systems
920 South Andreasen Drive #104
Escondido, CA 92029
Phone: (800) 552-5058
WWW.DELTATSALES.COM

Niagrow Systems, Inc.
4300 Stanley Avenue
Niagara Falls ON L2E 6T7
Canada
Phone: (905) 357-6500
WWW.NIAGROW.COM

Ventilation Systems

Acme Engineering & Manufacturing Corporation
PO Box 978
Muskogee, OK 74402
Phone: (918) 682-7791
WWW.ACMEHORT.COM

American Coolair Corporation
PO Box 2300
Jacksonville, FL 32203-2300
Phone: (904) 389-3646
WWW.COOLAIR.COM

Hired-Hand Green, Inc.
PO Box 99
Bremen, AL 35033
Phone: (256) 287-7777
WWW.HHGREEN.COM

Schaefer Ventilation Equipment
3423 County Road 74
St. Cloud, MN 56301
Phone: (320) 251-8696
WWW.SCHAEFERFAN.COM

Watering Systems

Andpro Limited
272 Church Street West
Waterford ON N0E 1Y0
Canada
Phone: (519) 443-4411

Cherry Creek Systems
745 Valley Street
Colorado Springs, CO 80915
Phone: (719) 380-8373
WWW.CHERRYCREEKSYSTEMS.COM

DGT Volmatic North America, Inc.
5311 Creek Shadows
Kingwood, TX 77339
Phone: (888) 915-6464
WWW.VOLMATIC.COM

Growing Systems, Inc.
2950 North Weil Street
Milwaukee, WI 53212
Phone: (414) 263-3131

GTI Greenhouse Technology, Inc.
111 Squires Alley
Richmond, KY 40475
Phone: (859) 626-3001

ITS Equipment/McConkey Co.
1615 Puyallup Street
Sumner, WA 98390
Phone: (253) 863-8111
WWW.ITSBOOMS.COM

Midwest GROmaster, Inc.
PO Box 1006/7N 268 Route 25
St. Charles, IL 60174
Phone: (847) 888-3558
WWW.MIDGRO.COM

D Useful Conversions

TABLE D-1. Useful conversions

Type of measurement	To convert:	Into:	Multiply by:
Length	centimeters (cm)	inches (in)	0.394
	feet (ft)	centimeters (cm)	30.48
	feet (ft)	inches (in)	12
	feet (ft)	yards (yd)	0.33
	inches (in)	feet (ft)	0.083
	inches (in)	millimeters (mm)	25.4
	inches (in)	centimeters (cm)	2.54
	meters (m)	inches (in)	39.37
	meters (m)	feet (ft)	3.281
	meters (m)	yards (yd)	1.094
	yards (yd)	feet (ft)	3
	yards (yd)	centimeters (cm)	91.44
	yards (yd)	meters (m)	0.9144
Area	acres	square feet (ft^2)	43,560
	acres	square yards (yd^2)	4,840
	acres	hectares (ha)	0.4047
	hectares (ha)	acres	2.471
	hectares (ha)	square meters (m^2)	10,000
	square inches (in^2)	square centimeters (cm^2)	6.452
	square centimeters (cm^2)	square inches (in^2)	0.155
	square feet (ft^2)	square centimeters (cm^2)	929.09
	square feet (ft^2)	square meters (m^2)	0.0929
	square meters (m^2)	square feet (ft^2)	10.76
	square meters (m^2)	square yards (yd^2)	1.196

continued on next page

TABLE D-1. Useful conversions (continued)

Type of measurement	To convert:	Into:	Multiply by:
Weight	grams (g)	ounces (oz)	0.0353
	kilograms (kg)	pounds (lb)	2.205
	metric tons (megagrams)	short tons	1.1023
	ounces (oz)	pounds (lb)	0.0625
	ounces (oz)	grams (g)	28.35
	pounds (lb)	ounces (oz)	16
	pounds (lb)	grams (g)	453.6
	short tons	metric tons (megagrams)	0.9078
Volume, solids	bushels (bu)	cubic feet (ft^3)	1.24
	bushels (bu)	cubic meters (m^3)	0.352
	bushels (bu)	liters (L)	35.24
	cubic feet (ft^3)	liters (L)	28.32
	cubic feet (ft^3)	U.S. gallons (gal)	7.48
	cubic feet (ft^3)	cubic inches (in^3)	1,728
	cubic feet (ft^3)	cubic yards (yd^3)	0.037
	cubic feet (ft^3)	bushels (bu)	0.804
	cubic inches (in^3)	milliliters (ml)	16.39
	cubic meters (m^3)	cubic yards (yd^3)	1.308
	cubic meters (m^3)	U.S. gallons (gal)	264.2
	cubic meters (m^3)	cubic feet (ft^3)	35.3
	cubic yards (yd^3)	cubic feet (ft^3)	27
	cubic yards (yd^3)	liters (L)	764.6
	cubic yards (yd^3)	cubic meters (m^3)	0.765
	cubic yards (yd^3)	bushels (bu)	21.7
	gallons, U.S. dry (gal)	cubic inches (in^3)	269
	liters (L)	cubic inches (in^3)	61.02
	milliliters (mL)	cubic inches (in^3)	0.0610
	quarts, dry (qt)	cubic inches (in^3)	67.2
Volume, liquids	cubic centimeters (cm^3 or cc)	milliliters (mL)	1
	cups (c)	fluid ounces (fl oz)	8
	gallons, U.S. (gal)	cups (c)	16
	gallons, U.S. (gal)	cubic inches (in^3)	231
	gallons, U.S. (gal)	quarts (qt)	4
	gallons, U.S. (gal)	liters (L)	3.785
	gallons, U.S. (gal)	gallons, Imperial (gal)	0.833
	gallons, Imperial (gal)	cubic inches (in^3)	277.42
	gallons, Imperial (gal)	liters (L)	4.546
	gallons, Imperial (gal)	gallons, U.S. (gal)	1.20
	liters (L)	pints (pt)	2.113
	liters (L)	quarts (qt)	1.057
	liters (L)	gallons, U.S. (gal)	0.2642

continued on next page

TABLE D-1. Useful conversions (continued)

Type of measurement	To convert:	Into:	Multiply by:
Volume, liquids	milliliters (mL)	fluid ounces (fl oz)	0.0338
(continued)	pints (pt)	fluid ounces (fl oz)	16
	pints (pt)	cups (c)	2
	pints (pt)	quarts (qt)	0.5
	pints (pt)	cubic inches (in^3)	28.87
	pints (pt)	liters (L)	0.4732
	fluid ounces (fl oz)	cubic inches (in^3)	1.805
	fluid ounces (fl oz)	tablespoons (Tbsp)	2
	fluid ounces (fl oz)	teaspoons (tsp)	6
	fluid ounces (fl oz)	milliliters (mL)	29.57
	quarts (qt)	fluid ounces (fl oz)	32
	quarts (qt)	cups (c)	4
	quarts (qt)	pints (pt)	2
	quarts (qt)	U.S. gallons, liquid (gal)	0.25
	quarts (qt)	cubic inches (in^3)	57.7
	quarts (qt)	liters (L)	0.9463
	tablespoons (Tbsp)	teaspoons (tsp)	3
	tablespoons (Tbsp)	milliliters (mL)	15
	teaspoons (tsp)	milliliters (mL)	5
Flow volume	cubic feet/second (ft^3/s)	cubic meters/minute (m^3/min)	1.6990
	cubic feet/second (ft^3/s)	cubic meters/second (m^3/s)	0.0283
	gallons/hour (gal/h or gph)	liters/hour (L/h)	3.7854
	gallons/minute (gal/min or gpm)	liters/minute (L/min)	3.7854
	gallons/second (gal/s or gps)	cubic meters/second (m^3/s)	0.0037854
	gallons/second (gal/s or gps)	liters/second (L/s)	3.7854
Weight per volume	grams/cubic centimeter (g/cm^3)	pounds/cubic foot (lbs/ft^3)	62.3
	tablespoons/bushel (Tbsp/bu)	pounds/cubic yard (lbs/yd^3)	1 (approx.)
	pounds/cubic yard (lbs/yd^3)	ounces/cubic foot (oz/ft^3)	0.6
	ounces/cubic foot (oz/ft^3)	pounds/cubic yard (lbs/yd^3)	1.67
	pounds/cubic yard (lbs/yd^3)	grams/liter (g/L)	0.595
	kilograms/cubic meter (kg/m^3)	pounds/cubic yard (lbs/yd^3)	1.6821
Energy	British thermal unit (Btu)	kilojoule (kJ)	1.0551
	foot-pound (ft-lbf)	joule (J)	1.3558
	kilocalorie (kcal)	kilojoule (kJ)	4.1868
	boiler horsepower (BHP)	British thermal unit (Btu)	33,475
Pressure	inches of water (in H_2O)	kilopascals (kPa)	0.2488
Light	See page 58.		

Temperature Conversion Formulas

- To convert degrees Centigrade (˚C) to degrees Fahrenheit (˚F): (˚C x 9/5) + 32 = ˚F
- To convert degrees Fahrenheit (˚F) to degrees Centigrade (˚C): (˚F – 32) x 5/9 = ˚C

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White, J. W. and R. A. Aldrich. *Greenhouse Energy Conservation*. University Education Bulletin 80–530. University Park, PA: The Pennsylvania State University. 1980.

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Web site: WWW.NRAES.ORG

Greenhouse Engineering, NRAES–33

This book contains information needed to plan, construct, and control the commercial greenhouse. Major sections describe various structures, methods of materials handling, the greenhouse environment, and energy conservation. Other topics include plans for noncommercial greenhouses, access for the handicapped, and remodeling existing greenhouses. (212 pages, 1994)

Greenhouse Systems: Automation, Culture and Environment , NRAES–72

This proceedings from an international conference provides in-depth information on the engineering principles of greenhouse system design and management. Papers cover fundamentals and describe the application of those fundamentals in system selection. (306 pages, 1994)

Greenhouses for Homeowners and Gardeners, NRAES–137

This book covers every aspect of designing and constructing a home greenhouse — from foundations and utilities to bench design and lighting systems. It will enable both aspiring and practicing greenhouse operators to make informed decisions about foundations, glazing and framing materials, space utilization, interior design, heating and cooling systems, supplemental lighting, watering and fertilizing systems, and other design and construction issues. The book is amply illustrated and includes 10 greenhouse construction plans. (214 pages, 2000)

Herbaceous Perennials Production: A Guide from Propagation to Marketing, NRAES–93

This book covers the diversity of situations encountered by perennial growers in businesses of all sizes. Key chapters discuss production systems and schedules; propagation (including media, nutrients, environmental requirements, and methods); plug production; transplant and seedling care; nursery and field production; pest control (including deer and small animals); and forcing out-of-season bloom. Appendixes cover propagation methods and requirements for hundreds of species and optimum germination conditions for specific perennials and biennials. Thirty-eight figures and 45 tables supplement the text. (208 pages, 1998)

On-Farm Agrichemical Handling Facilities, NRAES–78

This publication discusses considerations a farmer should make regarding agrichemical storage, principal parts of the facility, storage environmental requirements, safety requirements, and storage alternatives. Included are two appendixes: one is a plan for a post-frame chemical storage building, and another is a list of companies that distribute equipment for storage or containment of chemicals. Also included are one table, 17 figures, and conversion factors. (22 pages, 1995)

On-Farm Composting Handbook, NRAES–54

The *On-Farm Composting Handbook* contains everything you ever wanted to know about composting on the farm — why to compost (the benefits and drawbacks), what to compost (raw materials), how to compost (the methods), and what to do if something goes wrong (management). The ten meticulously organized chapters also discuss site and environmental considerations, using compost, and marketing compost. Highlighting the text are 55 figures, 32 tables, and sample calculations for determining a recipe and sizing a compost pad. This book is so informative and comprehensive, it is used as a college textbook. (186 pages, 1992)

Post-Frame Building Handbook: Materials, Design Considerations, Construction Procedures, NRAES–1

This handbook includes chapters on materials, design considerations, and construction procedures for modern post-frame buildings. Materials discussed include lumber, posts, engineered wood products, roof trusses, roofing and siding, doors, and more. Detailed in the design considerations chapter are site selection, functional planning, structural loads, stresses in wood, diaphragm action, post size and spacing, foundations, framing members, suspended floors, and bulk storage of commodities. Construction procedures include layout and excavation, concrete footing pads, posts and poles, girders, trusses and construction braces, purlins and permanent braces, roofing, and siding and finishing. Sixty-two line drawings and 31 tables supplement the text. (78 pages, 1997)

Refrigeration and Controlled Atmosphere Storage for Horticultural Crops, NRAES–22

Refrigerated storage extends the period of acceptable eating quality of perishable seasonable products. General construction procedures for storage facilities are discussed in this book, such as site selection, structural considerations, thermal insulation, vapor barriers, and attic ventilation. Different refrigeration systems are explained, including descriptions of equipment and operating procedures. (44 pages, 1990)

Sprinkler Irrigation Systems, MWPS–30

Written from a midwestern perspective and with an emphasis on center-pivot systems, this guide provides a systematic approach to the whys and hows of developing sprinkler irrigation systems. It was developed as a planning tool, reference, and design manual for a broad audience, including agricultural producers and consultants, engineers, equipment dealers, government employees, educators, and students. Ten chapters cover the following topics: planning; system design; water sources; sprinkler systems; sprinkler characteristics; sprinkler selection and management; pumps, piping, and power units; chemigation; sprinkler application of effluent; and design examples. Includes over 110 photos and illustrations and 70 tables. (250 pages, 1999)

Trickle Irrigation in the Eastern United States, NRAES–4

This book was developed for humid climates and is an excellent planning and installation guide for growers considering a trickle irrigation system. Information is provided on plant-soil-water relationships, system components, specific crop recommendations, and system planning. Twelve tables and 19 figures supplement the text. (24 pages, 1985)

Water and Nutrient Management for Greenhouses, NRAES–56

This publication will help greenhouse managers learn the skills needed to manage a greenhouse for zero runoff. The book begins with a discussion of general crop needs, balancing nutrient applications with demand, and fertilizer measuring units. Subsequent chapters detail specific components of the root zone: water, fertilizer, substrate, temperature, and the biotic environment. Fifty-three tables and 15 figures supplement the text. (220 pages, 1996)

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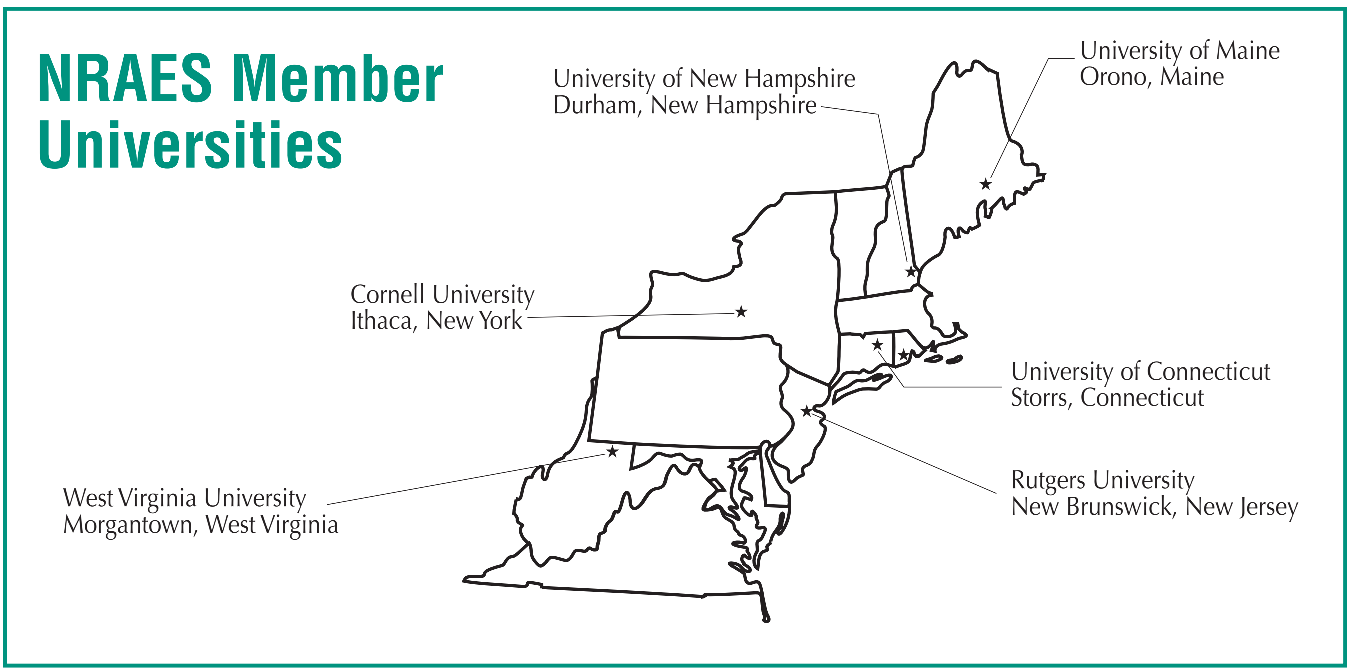

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