absorption of the solar radiation. A layer of circulating air is passed through the collector, and this air absorbs heat from the absorber plate. The heat is stored in the greenhouse rockpile.

The second system of solar heating is the use of solar hot water heating. This concept of solar heating requires the installation of a large insulated hot water tank and the installation of a series of solar collectors with a sufficiently large surface area to heat the water to a suitable temperature (Figure 5, below).

The use of bench and underfloor heating systems utilizing water at temperatures between 40 and 50°C for circulation are tailor-made for solar hot-water heating, since even in the middle of winter it is possible to heat water to these required temperatures by solar means.

A number of large-scale experimental solar hot-water heating systems are in use, and to date their performance has been satisfactory. The major concern with all solar heating systems is the very high capital costs. This problem must be addressed by a search for lower-cost construction materials and techniques if solar heating is to become widespread in the nursery industry.

A NEW CONCEPT IN GREENHOUSE DESIGN

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Classical greenhouse design consisted of vertical sides and sloping roof much like frame homes and other utility buildings, only covered with glass. Glass provided good light transmission but had many air leaks. With the development of fiberglass, many glass greenhouses were converted following hail or wind damage, but greenhouse design changed very little. In the 1960s double polyethylene film plastics with air blown between the layers provided the emphasis for change. The natural curvature of a quonset structure allowed the polyfilms to be used with a minimum of corners or edges where tearing could easily occur.

Both the classical and the quonset designs had a maximum exposure of the glass or plastic covering to the elements. As a result of the very low insulating values, heat loss was tremendous. Conventional design generally had the advantage of roof and side vents to provide natural convection cooling. On the other hand, double polyfilm quonset-style greenhouses could be very tight in terms of air infiltration and air loss but were difficult to ventilate and cool. Low-cost electricity and improved exhaust fans encouraged the use of pad and fan evaporative cooling systems. Some cooling was accomplished but considerable electricity and high-maintenance cooling pads were required to do so.

When the cost of energy began to escalate in the 1970s, it became painfully obvious how inefficient greenhouses were. With a maximum surface exposure and an R factor* of about one, many greenhouse owners, especially in northern climates, went out of business.

Air-inflated poly over glass or fiberglass increased the R of the sides or roof of a greenhouse to about two, but even so, the heating requirements were staggering. Night-insulating curtains provided a major benefit but had the added complication of needing to be opened and closed daily. A general "tightening up" of the greenhouse and the addition of air-lock doors provided further savings. In most new construction and some older structures, north walls were converted to insulated conventional construction, much like the wall of a home, with little, if any, sacrifice in plant growth.

All of these energy-saving features were beneficial, but the savings did not keep up with climbing energy costs. Then came the emphasis on solar heating. In print and theoretically it sounds terrific. The sun *does* provide an awesome source of energy.

Solar collectors can collect vast quantities of heat when the sun shines, even when air temperatures are very low. The problem is how to store enough energy economically to last for the night or succeeding days when the sun does not shine. Many agricultural engineers, horticulturists, and others scrambled to refine and perfect a successful solar-heated greenhouse. Variations in solar collectors, heat storage, and insulating systems were numerous. However, the construction of these systems was expensive and awkward, and maintenance was high. For example, we designed a floor-heated, floor-heat-storage greenhouse, which used the space between the inner two layers of a triple layer air-inflated poly cover as the solar collector. Fuel consumption was reduced by nearly 70% compared to a conventional forced-air, natural gas-heated poly-covered quonset greenhouse of the same dimensions. However, during that winter there were two periods when conventional heating was required for periods of 6 and 11 consecutive overcast days, even though it was a very mild winter in north central Oklahoma. The following winter energy savings were only 43%.

FACTORS CONSIDERED AND DESIRED

The ideal greenhouse would have a minimum of opaque surface for heat buildup in the summer and heat loss in winter. It would have good ventilation and cooling. It would provide a

*Resistance of wall materials to heat transmission as compared to transmission through glass.

minimum uninsulated area for heat loss, yet enough light for the array of crops to be grown. If a cold weather insulation system is used it should be easy to operate and effective with a minimum of maintenance and expense.

Through experiments and experience, it was observed that up to a point the east and west walls of a greenhouse could be made of solid insulated materials like the north wall with little or no loss in crop performance and quality. This is due to the low sun angle during the winter months, which limits early-morning and late-evening light intensity.

Heat would be with fossil fuels, but the heat placement would be below the root zone of the crop. Forced-air heating stirs and maximizes the movement of warm air against the poorly-insulated light-admitting surfaces. On the other hand, a static bottom-heat system on which containers are placed heats most at the bottom of the container and least near the surface. Evaporative cooling occurs as water is lost from the surface of the growth medium. The temperature gradient from top to bottom of the container is therefore substantial. If the bottom heat is raised to the point where the surface of the growth medium is near 70°F, the roots in the bottom will be killed by excess heat. In spite of these complications, a static bottom-heat system holds the edge over forced-air heaters.

The ventilation system should work with the natural convective movements of warm and cool air instead of against them. Work with the roof vents in the quonset structures clearly demonstrated the advantage of roof vents. However, to be practical the greenhouse design must be such that vents can be provided in the high points.

THE FINAL DESIGN

A modified sawtooth design with the vertical surfaces facing south was chosen after all factors were thoroughly considered. By adjusting the height and slope of the sawtooth sections, good winter lighting could be obtained with a minimum of heat-loss surfaces. The sloping roof surface could be insulated in the fall and allowed to remain until spring. Thus no daily open-close curtains or apertures are involved. The peaks of a sawtooth design provide a natural ventilation point to discharge excess heat. If shade during the warm months is desired, it can remain in place the year round. During the summer the shade is effective in blocking out part of the sun, which at that time is overhead. On the other hand, in winter the sun has moved south so that all light enters the vertical face of the sawtooth. The sloping and shaded surface can, therefore, be insulated. The north, east, and west walls are insulated to $R = 11$ to a height of seven feet. The south wall is insulated up to the height of the containers sitting on the benches. Standard home-construction materials are used.

The interior of these solid walls is covered with reflective materials to diffuse light and minimize shadows. The heating system uses hot water in PVC pipe but without direct contact between the bottom of the container and the surface of the pipe. Using schedule 40 1-in. instead of ½ or ¾ in. PVC pipe on 5-in. centers will increase the system's capability to buffer temperature change. In addition, insulation is placed below the heat pipes in order to minimize downward heat loss.

THE STRUCTURE

The structure, oriented east-west, is 24 ft. by 60 ft. (two 12-ft. sections), with a frame and support posts of pressure-treated lumber. The 4-in. by 4-in. support posts are on 6-ft. centers along the north, center, and south walls with 12 ft. between rows. The 33 posts are set in concrete approximately 2 ft. deep. Headers of 2-by-4s, creating an L-shape, are constructed to connect the posts along the east-west axis.

The roof trusses are designed so that three 12-ft. 2×4's are used with no waste. The north wall is solid as are the east and west walls up to the base of the truss. These walls consist of 2-by-4s framing and ⅝-in. thick grooved fir siding on the outside and R-11 fiberglass insulation and corrugated galvanized steel on the inside. The corrugated steel is oriented vertically so that, as the sun moves across the horizon and strikes the many curved surfaces, light is reflected in all directions, especially off the inner north wall.

The south wall up to the bench height is also insulated. However, foil-faced urethane sheets were used, since the likelihood of moisture contact is greater.

The roof covering of choice was polygal polycarbonate in 4-by-12 ft. sheets. This provides a tough, durable surface with reasonable insulating qualities, good light transmission, and an acceptable cost.

Ten 12-in. non-powered, turbine roof vents were positioned at the peaks of the roof. There are four air inlets on the ends and along the south wall. Air transfer from outside into the greenhouse occurs as a result of natural convection.

The heating system consists of two 30-gal. propane-fired hot water tanks with a capacity of 37,000 BTUs each (output). The warm water is circulated by small in-line, centrifugal pumps approximately ⅛ horsepower through 1-in. schedule 40 PVC pipe on 5-in. centers.

Water temperature is controlled by the thermostat on the heater. Water flow and bench heating are controlled by a thermostat that controls the pump. This dual thermostat protects both the plants and the pipes from excess heat, while using a minimum of controls.

Wire-mesh panels 52-in. by 16-ft. (cattle panels) were placed below and on top of the 1-in. PVC lines to provide support for the PVC and a surface for flats or trays of containers. This ensures that no container is in contact with the PVC line; thus heat is transferred by air rather than by direct conduction. Foil-faced, ½-inch urethane insulation was placed beneath the benches to minimize downward heat loss due to convection.

PRIMING THE WATERING-HEATING SYSTEM

One of the greatest challenges with this system is removing all air from the hot water tank, pipe, header, and pump complex. If an upright water tank is used, install a vertical vent pipe at the high point of the system, including a threaded and fitting and screw-thread cap. Leave the cap off until start-up time. Be sure the tank is equipped with a pressure-relief valve.

Once the system is functioning properly, check all connections for leaks, including the cap on the vent pipe. Water can be removed from the system down to where it just reaches the bottom of the vent pipe. Replace the cap. This leaves the air in the vent pipe to be compressed as the water expands due to heating. However, this does not appear to be necessary since the PVC pipe expands more than the water upon heating. If the system is ever to be left unused in winter, automobile anti-freeze may be added to prevent damage.

PERFORMANCE

The winter of 1986–87 was mild for north central Oklahoma. The ½-in. thick foil-faced insulation sheets were installed in the roof on November 9. No reduction in light occurred because the sun was so far south. There were no shadows visible in the greenhouse as a result of diffusion and reflection provided by the design.

The coldest temperature outside was 9°F (−13°C) while the lowest temperature inside was 47°F (+7°C) even though only one hot water tank was used with lines in one of the four benches. A 12-in. snow in January filled the valleys of the roof, but no load problem could be detected.

CHANGES CONSIDERED

If the structure was rebuilt today, the vertical height of the saw-tooth would be 6 ft. instead of 4 ft. and truss length would be 16 ft. This would allow the insulation to be installed a few weeks earlier and stay later. In addition, some sunlight would be reflected off the underside of the insulation and straight down onto the benches. Additional air inlet vents would be built into both ends along the south side to assist natural convection ventilation. All other factors would remain the same. It is important to note that this is an experimental structure and has been in use for only one year as of this writing. Additional adjustments in the design and function may become apparent with time.

Details of construction and priming the water-heating system are available from the author.

DEVELOPMENT OF A NATURAL VENT GREENHOUSE

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The development of a natural vent greenhouse is one in a series of developments aimed at more efficient plant propagation in my particular set of circumstances. Development of the concept of this house began in 1977.

Up until then, my nursery's efforts were almost exclusively to produce citrus in several sizes for dooryard sales through retail outlets. Planned expansion of woody ornamental production on 25 acres mandated the development of efficient buildings and production tools for the specific purpose of propagation. At this time (1977) most woody ornamental propagation in Florida was done in open sun under mist using a peat bed or rose pots with a peat:perlite medium.

As recently as 1970, there was opposition to including a propagation unit inside greenhouses at Florida vocational schools as county commissioners felt putting a propagation unit inside a greenhouse was a huge waste. However, seeing production problems throughout the state convinced me that efficient climate control was essential with woody ornaments even in Florida's subtropical climate.

The style of the buildings that I saw the pepper growers build in Webster, Florida, appeared to be efficient. A very innovative structure seen at Wetherwood Nursery in Dover, Florida proved the desirability and versatility of the new innovation of double poly covering. The development of double poly covering has made it possible to construct a very inexpensive, but effective propagation structure. Ventilation comes in through openings the length of the house on the side and out through gable ends.

Nine wood-frame structures were eventually constructed in 1978–79 using this basic plant at a cost of approximately $1,500 per building. The amount seemed reasonable in light of the fact that we