CONSTRUCTION AND OPERATION OF A SOLAR HEATED RESIDENCE/GREENHOUSE COMBINATION

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ABSTRACT

A solar heated residence/greenhouse combination structure has been developed and operated during the 1976-1977 heating season by the Solar Energy Applications Laboratory at Colorado State University. The greenhouse is situated on the south side of the structure with a solid wall separating it from the residence area. Each area comprises 640 square feet (59.5 square meters) with 450 square feet (42 square meters) of growing area in raised benches.

Solar heat is collected by forced air through the greenhouse and flat-plate solar collectors and stored as sensible heat in a rock bed for nighttime or cloudy day use. The solar system was started up on December 10, 1976, and has operated without interruption since that date. Performance data have been obtained and are reported. Operational and construction characteristics of this solar project are also documented.

INTRODUCTION

The objective of the solar greenhouse and residence project at Colorado State University is to determine the compatibility of residential and garden greenhouse spaces combined in the same structure. In addition, solar energy is utilized as the primary heating source for the combination building.

Architects, realizing the appeal of plants in or near living quarters, often design some form of greenhouse area incorporated into residential buildings. The requirement for such greenhouse space is quite simple—transparent walls and roof which are exposed to the southern direction for winter sunlight. The difficulty lies in maintaining the greenhouse within acceptable temperature limits. Greenhouses will overheat during a cold but sunny afternoon. At night the heating requirements become very high for the greenhouse, due to the obvious lack of insulation, demanding perhaps five or more times the heat for a house of the same size.

Depending upon how a person or family considers the value of their time, home greenhouse gardening can produce high quality produce at a savings. Such savings can be lost, however, due to fuel costs necessary to heat
the greenhouse. A solution to heat savings lies in reducing the heat loss by "tight" greenhouse construction and, secondly, by utilizing any excess solar heat generated in the greenhouse during the day to be applied to heating at night. Heat loss can be cut to one-half or less of that for conventional greenhouse structures without excessive cost or elaborate methods. With such construction, the greenhouse becomes a solar collector with substantial excess heat during sunny periods. This heat may then be transferred to a rock box and stored for night time heating of the greenhouse or house. Flat-plate solar collectors are optional, but may be applied to achieve 70 percent or more of heating demand supplied by solar energy.

PRINCIPLE OF THE SOLAR HEATED GREENHOUSE/RESIDENCE COMBINATION

A combined residence/greenhouse solar heating system can be constructed which will enhance the overall performance of the solar system when compared with solar heating of the residence or greenhouse alone. This is due to two factors. First, the heating demands of the greenhouse and residence are not on the same diurnal or seasonal schedule. Therefore, "excess" solar heat, with respect to one, may be supplied to the other, an obvious advantage. Secondly, the greenhouse can tolerate greater temperature excursions than are acceptable in the residence. The greenhouse may be warmer during the day and cooler at night than the home and in fact, many plants benefit from this diurnal temperature cycle. The advantage of this greenhouse temperature cycle relative to the home derives from two fundamental conditions, that of increased solar heat recovery at lowered temperature and thermal stratification in the solar heat storage. A solar air heating system with a pebble-bed storage unit will sustain a large temperature gradient (thermal stratification) in the direction of air flow through the bed, as indicated in Figure 1, from actual measurement. This thermal stratification is developed by flowing the solar heated air in one direction (i.e., from the top to the bottom) and reversing the flow of air for heat removal (i.e., from bottom to top). Liquid storage tanks, by contrast, are quite difficult to stratify, and also liquid must be passed through a duct coil unit to effect space heating.

Thermal stratification assists both solar collection and space heating of the house-greenhouse combination. Air at the lowest useful temperature (i.e., the greenhouse at night) is delivered to the solar collector. In addition, air is delivered to the house or greenhouse from the pebble-bed at the highest collector operating temperature. The highest collector operating temperature will be dependent upon the collection conditions (radiation levels, outdoor temperature, wind, etc.) and the air flow rate.

APPLICATION TO LARGE GREENHOUSES

The commercial greenhouse operator would normally have a much larger greenhouse than his own house. It would then be advisable to combine
Figure 1. Pebble-Bed Thermal Stratification Variations

Air Circulation Started 9:30
Air Circulation Ended 16:30
Downward Air Flow
the greenhouse with a larger commercial or institutional building. If such buildings are unoccupied at night, they would compliment the greenhouse better than a residence, because more of the stored solar heat for night time heating may be applied to the greenhouse. The building could be any building which requires space heating, but would likely be functionally related to the greenhouse, such as a horticulture building or a vegetable processing plant.

APPLICATION TO COOL, DRY CLIMATE

The cool dry climate is characterized by large diurnal temperature change and cool temperatures combined with clear skies. While heating requirements are high (often 6000 to 10,000 degree-days), the solar conditions are extremely favorable (refer to Figures 2 and 3).

In this climate a well-constructed greenhouse receives excess solar heat during solar hours, even in midwinter. At night, however, the heat load is high due to low surface temperatures and radiation to clear skies. A definite advantage is seen by coupling the greenhouse to a residence with heat storage. The diurnal extremes of the greenhouse are buffered by this arrangement and maximum advantage is taken of all available solar insolation.

GREENHOUSE CONSTRUCTION

Greenhouse construction methods were employed at the Colorado State University solar greenhouse, which have reduced the heating requirements to less than one-half that of a conventional greenhouse. These include double glazing, caulking, and perimeter insulation in the ground. Combining the greenhouse with the house also reduces the heat loss because the north wall of the greenhouse is shared with the house and, consequently, heat is not lost through that wall.

The greenhouse roof consists of 3 by 6.5 foot (.9 by 2 meter) double glass units which are supported on redwood 4 by 4 inch (10 by 10 cm) rafters on 3 foot (.9 meter) spacing and a pitch of 10 in 12, or approximately 40 degrees from the horizontal. The greenhouse glass roof and solar collectors are depicted in the photographs of Figures 4 and 5. The glass units are hermetically sealed to prevent the entrance of moisture or other foreign material, with a sealed air space of .75 inch (1.5 cm) thick.

The end walls and three foot (one meter) high south wall are made of double thickness corrugated fiberglass. Glass was not used on the walls because of the irregular shape, which required cutting and fitting of the fiberglass and also because of the breakage hazard of glass close to the ground. Five-ounce Tedlar coated fiberglass was selected with spacing and weather seal between fiberglass sheets provided by .5 inch (1 cm) diameter butyl rubber strips. The inner layer of fiberglass was installed,
Fig. 3. Estimated average solar and sky radiation in gram calories/cm²(day) incident upon a south-facing vertical surface (Figures 12 and 13 on page 119 of the December, 1953, issue of Heating, Piping, and Air Conditioning).
followed by the butyl rubber strips, and finally the outer fiberglass layer was applied. The dual fiberglass walls could also be preassembled before installation if dimensions are not too intricate. It is critical in either case that the perimeter of the fiberglass be completely sealed against the intrusion of water or dirt. The corrugated ends were sealed with neoprene rubber fill strips, which are supplied with the fiberglass. All cracks and holes in the wall which could allow air infiltration were filled afterward with silicone caulking.

Perimeter insulation was placed on the ground below the greenhouse walls to reduce ground heat loss. The insulation consisted of 1.5 inch (5 cm) of styrofoam board, sandwiched between two pieces of .5 inch (1 cm) inch asphalt impregnated sheathing. The insulation reached 16 to 22 inches (40 to 56 cm) below grade.

These energy conserving features, in addition to the elimination of heat loss from the north wall of the greenhouse (this is the house wall), reduced the heating demand substantially. Also, outdoor air was never brought into the greenhouse when it was being heated. The calculated heat loss (which was verified by the heat load data), is 20,930 Btu per degree-day (3.4 kWh/°C-day), or 32.7 Btu/DD per square foot of greenhouse. This compares with 60 Btu/DD·ft² or high for typical commercial greenhouses.

GREENHOUSE OPERATION

Vegetable and foliage plants are grown in raised benches totaling 450 square feet (42 square meters) of actual growing area. Growing is done by the hydroponics method in #2 chip gravel, with water and nutrients applied every four hours by trickle irrigation. See Figure 6.

A two-stage thermostat is set at 58°F (14.5°C) and 54°F (12.2°C) for heating. The solar heat from the rock box is applied at the 58 degree point. If the greenhouse temperature should fall to 54°F (14.5°C), a natural gas burner comes on to supplement the solar heat.

Cooling of the greenhouse is accomplished by ventilation with or without evaporation pads. A two-stage cooling thermostat is set at 80°F (26.7°C) and 90°F (32.2°C). At 80°F the fans come on to ventilate the greenhouse with outdoor air. At 90°F, water is admitted to evaporation pads which cover the air intakes. With the double glazed greenhouse, cooling is necessary during warm sunny days in the winter as well as summer.

ENERGY RELATED FACTORS

Several factors affect the heating requirement of any structure, however, there are some unique aspects which have been identified on this particular structure. Winds in the region create a very high heat load on any structure, and particularly on a greenhouse. A 40 mph (64.36 km/hr)
wind blowing at 40°F (4.5°C), which is not unusual at the project site, results in the same heating load for the greenhouse as the design temperature of -10°F (-23.3°C) with no wind. The greenhouse receives no protection from the wind because there are no adjacent trees, fences, or other structures to resist wind. The residence on the north side does, however, spare the greenhouse from exposure to wind on that side.

Humidity levels in the greenhouse are another important heat load factor. The moisture condenses on the greenhouse roof and walls at night, giving off the latent heat to the walls, which in turn convect and radiate the heat to the outside. A layer of moisture adheres to the surface, but most of it drips or runs to the floor of the greenhouse. The trickle irrigation system and gravel growing benches reduce the amount of atmospheric humidity in the greenhouse. Therefore less moisture is condensed on the greenhouse walls and less heat is lost by this mechanism. The lowered humidity is also useful in maintaining the desirable humidity in the residence.

Eighty gallons (300 liters) per day of water are used for watering the greenhouse plants. This water is brought in at 50°F (10°C) and is heated to 65°F (18.3°C) in the gravel beds. Consequently, 10,000 Btu (2093 kWh) are consumed as water heating in the greenhouse.

GREENHOUSE PRODUCTION

Vegetables were brought into the greenhouse during the first week in December. Some were transplanted as two- to four-week old plants, and others were seeded at that time. Flowering plants were also grown in hanging pots suspended from the greenhouse rafters. Table 1 is a summary of the greenhouse plant production.

RESIDENCE CONSTRUCTION

The residence space is constructed to current Federal Housing Administration (FHA) insulation standards for residential buildings in the northern Colorado region. This consists of R = 11 ft²·°F·hr/Btu for the frame walls and foundation walls, and R = 19 ft²·°F·hr/Btu in the ceiling. Two windows (40 square feet) are exposed to the outside and five windows (100 square feet) are exposed to the greenhouse. All windows are wood frame double glazed. The 640 square foot (59.4 square meter) ground level and the open attic area are both heated with a heating load of 8,540 Btu per degree-day (1.4 kWh/°C·day).

The rock box is built into the residence and is supported on a 6 inch (15 cm) concrete slab located two feet below grade. The rock box requires 8 feet by 6 feet (2.4 by 1.8 meters) of floor space, however, the top of the rock box is used as the mechanical equipment area and is easily accessible through a door from inside the building.
<table>
<thead>
<tr>
<th>Variety</th>
<th>Days since transplant or seed</th>
<th>Total fresh weight</th>
<th>Square feet</th>
<th>Quantities</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Bantam Peas</td>
<td>116 (T)</td>
<td>385</td>
<td>52.5</td>
<td></td>
<td>Nutrient deficiencies due to fertilizer problems. Yellowing and reduced growth. Presently returning to production</td>
</tr>
<tr>
<td>Tenderpod Peas</td>
<td>114 (T)</td>
<td>552</td>
<td>52.5</td>
<td></td>
<td>Same as above</td>
</tr>
<tr>
<td>Broccoli - Green Comet Hybrid</td>
<td>80 (T)</td>
<td>647</td>
<td>99.0</td>
<td></td>
<td>Nutrient deficiencies resulted in reduced growth</td>
</tr>
<tr>
<td>Cauliflower Snow King</td>
<td>100 (T)</td>
<td>3343 4877</td>
<td>99.0</td>
<td>37 - split heads 21 - good heads</td>
<td>Same as above. Heat as high as 85°F has resulted in split heads</td>
</tr>
<tr>
<td>Lettuce - Salad Bowl</td>
<td>84 (T) (H)</td>
<td>4513</td>
<td>16.5</td>
<td>34 heads</td>
<td></td>
</tr>
<tr>
<td>Radishes - Comet</td>
<td>86 (S) (H)</td>
<td>2860</td>
<td>9</td>
<td>17.5 dozen</td>
<td></td>
</tr>
<tr>
<td>Black Zucchini Squash</td>
<td>73 (S)</td>
<td>320</td>
<td>18</td>
<td>1 head</td>
<td></td>
</tr>
</tbody>
</table>
RESIDENCE OPERATION

The residence portion of the building functions as a visitor center and a laboratory space rather than living quarters. This arrangement allows exposure to the public and facilitates the data and operational requirements of the project, while still representing a structure of residential construction for heat load considerations. Lighting, door openings, and human occupancy are typical of a residence during the daytime.

SOLAR SYSTEM OPERATION

When the solar collectors are sufficiently warmer than the rock box, a differential temperature control turns on the collector blower and also opens the collector damper. Air is then forced through the greenhouse and collectors to gather solar heat. The air is passed through the rock box if the house is not calling for heat (Figure 7, Mode 1). This solar storage process continues until the rock box temperature approaches the collector temperature. The differential temperature range is adjustable so that a proper compromise can be reached between solar heat collection and the blower power consumption. If the house thermostat calls for heat while solar heat is being collected, the hot air is directed to the house instead of the rock box (Figure 7, Mode 2).

Space heating is provided to the greenhouse and house as separate zones. Each zone has a two-stage thermostat. At 70°F or 21.1°C (first stage), the house thermostat turns on the house blower and opens the house damper. This directs air from the rock box to the house utilizing the stored solar heat (Figure 7, Mode 3H). If the temperature falls to 68°F or 20°C, the second stage thermostat turns on a gas burner to supplement the solar heat.

The greenhouse is heated by the same process as the house, except that the thermostats are set lower (Figure 7, Mode 3G). Solar heat is applied to the greenhouse at 58°F (14.4°C) and fuel is used at 54°F (12.2°C).

The solar heat delivered from the rock box is lower in temperature than from a fuel heater. Consequently, the blower must run longer to satisfy the heating demand. Electrical energy is somewhat higher for the solar heat as a result.

During the cooling season the collectors may be employed to help cool the greenhouse. By opening the collector outlet to the outdoors, air is drawn out of the greenhouse by convective flow. A manual damper is provided for this purpose, which will be left open during summer months.

SOLAR SYSTEM CONSTRUCTION

Solar collectors were purchased which were preassembled and ready to be placed on the roof. A standard roof with 2 by 8 rafters and .5 inch plywood was provided upon which to mount the collectors. The collectors
Figure 7. Modes of Operation
were installed by three workmen in two days. The finished collector installation includes cap strips and gaskets which prevent water leakage, and thus constitutes the weatherproof roof for the building. As shown in Figure 4, the greenhouse roof was integrated into the same plane as the collectors to save building cost and add to the appearance of the overall structure. The pitch of the collector and greenhouse roof is 10 in 12, or approximately 40 degrees from the horizontal, which is just equal to the latitude of the project site. The ideal angle for winter solar collection is approximately latitude plus 15 degrees, as shown in Figure 8, however the steeper angle would create an excessive elevation of the roof for this design. The slight sacrifice in performance (estimated at five percent) was considered tolerable. Snow accumulates to a maximum of one inch before it slides off the collectors and greenhouse to the ground.

The collectors are internally manifolded with four duct penetrations through the building subroof to bring air out of the collectors. Air enters the collectors from the greenhouse through four backdraft dampers which permit air to flow up into the collectors but prevent air from flowing in the reverse direction. This is done to avoid cold air in the collectors at night from draining down into the greenhouse.

The collectors are double glazed with sealed glass units, 3 feet by 6.5 feet, or .9 by 2 meters (the same as the greenhouse roof). A non-selective black coating with absorptivity of .97 is applied on 22 gauge steel as the solar radiation absorber. Air is forced beneath the absorber plate in a .5 inch (1.3 cm) deep duct to be heated. Air flow is 2 cfm per square foot (10 liters per second per square meter) of collector or 625 feet per minute (3.17 meters per second) velocity. The resulting Reynolds number at 120°F (49°C) air temperature based on the duct depth is 2100 in the collectors.

The collectors are insulated on the back and around the perimeter to minimize heat loss from these surfaces. There are 26 collector units with outside dimensions of 3 feet by 6.5 feet (.9 by 2 meters), for a total area of 507 square feet (47.1 square meters). The actual absorber area exposed to the sun rays is about 450 square feet (42 square meters) or 89 percent of the total area.

The collectors were allowed to reach stagnation temperature (probably 300°F (150°C) or higher) for three weeks prior to system start-up. The glass, coating, and other materials showed no sign of deterioration from this experience, however, summer ventilation will be employed to lessen the potential for deterioration under such high temperature conditions (see Solar System Operation).

Dirt, moisture, and wind have not affected the integrity or functioning of the collectors. Winds have gusted to 78 miles per hour (125 km/hr) without glass breakage. Blowing dust has also occurred with no perceptible penetration into the collector.
Figure 8. Effect of Collector Tilt on Total System Performance for a Typical Installation at 35°N Latitude

ROCK BOX

Solar heat is stored as sensible heat in rocks for delivery to the building during non-solar periods. The rock is screened between .75 and 1.5 inch (2 to 4 cm) in diameter. It is hard rounded stone which is sold locally as concrete aggregate. The heat capacity of the rock is .2 Btu per pound, degree F (.2 cal/gram·°C), and has a fill density of 100 pounds per cubic foot (1608 KG per cubic meter), or 20 Btu per cubic foot, degree F.

The rock box for the CSU solar greenhouse/residence contains 336 cubic feet (9.5 cubic meters) of 16.8 tons of rock. This quantity of rock is designed to store the maximum solar energy collected during a clear day, which is about 500,000 Btu (147 kWh) from both the greenhouse and solar collectors.

The duration of solar heating from storage is influenced by many factors, however, when the rock box is charged from a full day of solar collection, it will normally carry the heating load for 24 hours of winter weather without additional collection. Cloudy periods exceeding 24 hours are too infrequent at the site to justify the cost and space of a larger rock box for solar heating storage.

ROCK BOX DESIGN

The rock box is designed so that air will flow vertically through the rock. Hot air from the collectors enters the top of the box and flows downward. Greenhouse or house air enters the bottom and flows upward. The resulting temperature profile in the vertical direction is complex (see Figure 9), however it is always hotter near the top than at the bottom. The hot end is preferred at the top rather than the bottom because it is easier to insulate the top, and also because the equipment layout is simpler for this application. The disadvantage of the hot end at the top is that dampers and blowers are operating in the hot air streams, whereas they could be in the cold air streams with a reversed rock box.

A wood frame rock box 8 feet deep, 8 feet long, and 6 feet wide (2.44 by 2.44 by 1.83 meters) is used to contain the rocks. The back walls are constructed of 2 by 4 inch (5 by 10 cm) vertical studs at one foot spacing, which are covered on the inside with .75 inch (2 cm) plywood. The walls are tied together at the middle (four feet from the bottom) with steel crating bands which are spaced two feet (tied to alternate studs). The 3.5 inch (9 cm) thick space between studs is filled with bonded fiberglass insulation. The top of the box is insulated with one-inch high density fiberglass board with an aluminum scrimcoat facing the rock. Three-quarter inch plywood was placed over the fiberglass board, which is supported on 2 by 4 inch (5 by 10 cm) wood at two foot spacing. The top forms a platform upon which all of the mechanical equipment is mounted.
Figure 9. Pressure Drop Through a Rock Bin with .75 to 1.5 Inch Rocks
The floor of the rock box is a six-inch (15.2 cm) thick concrete slab with reinforcing steel mesh, capable of supporting the rock load without cracking. An air plenum must be provided at the bottom to allow proper air flow. This was accomplished by an array of concrete bond beam blocks on the floor with the webs pointing upward. An expanded metal screen with .75 inch (2 cm) hole size was placed over the blocks which support the rock while allowing proper air distribution at the bottom of the rock box.

The rock depth is important with respect to air pressure and the associated blower power. To determine the static air pressure in the rock box, it is first necessary to know the air flow rate for the system. This air flow is entered into the pressure drop curve of Figure 8. The design procedure is actually trial and error or computer solved because the depth and cross-section area can be varied while maintaining the same rock volume. The cross-section area for the CSU project is 48 square feet (4.46 square meters) and the air flow rate is 1000 cfm (471 liters per second). The pressure drop through the seven feet of rock depth, using Figure 8, is .14 inches (3.5 mm). This is in close agreement with the actual static pressure shown in Table 2.

SOLAR SYSTEM DESIGN

Sizing of the solar system was based on two factors; the portion of heating requirement to be provided by solar and the physical space available on the roof of the building upon which to place the solar collectors. The solution is actually then a compromise between what is the best economic size and what is acceptable in terms of space available or aesthetics. The optimum economic sizing of the solar system for this project was performed by a sizing procedure developed for solar space heating [1]. The procedure is not a topic of this paper, but may be obtained from the reference. From this procedure a solar heating capability corresponding to 70 percent of the annual heating demand for the combined structure was determined to be appropriate. The required collector area to accomplish this portion of the heating demand was computed from the climatic conditions of Fort Collins, Colorado and the estimated heat load for the residence and greenhouse. A solar collection area of approximately 500 square feet (46.5 square meters) was selected. The solar heat recovery from the greenhouse was less well defined, but was expected to contribute an additional 10 or 15 percent to the heat supply. The extent to which solar energy can be extracted from the greenhouse depends upon the upper temperature limit in the greenhouse. This is an operational or plant response limitation rather than a system limitation. Consequently, the greenhouse contribution could only be found by an operational or experimental determination.

Sizing of the rock box was discussed previously. It must be capable of storing the maximum solar collection during a full day of clear sky solar radiation. For the collectors this would require one-half cubic foot of rock per square foot of collector, or 250 cubic feet (7.06 cubic meters). The rock bed volume of 336 cubic feet (9.4 cubic meters) was provided.
Table 2
System Static Air Pressure

Solar Collection

<table>
<thead>
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<th>Description</th>
<th>Air flow:</th>
<th>Blower power:</th>
<th>Static air pressure (in W.G.)</th>
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<tr>
<td>Air flow</td>
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<td>370 watt</td>
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<tr>
<td>Blower power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collectors and backdraft damper</td>
<td></td>
<td></td>
<td>.45</td>
</tr>
<tr>
<td>Rock box and air filter</td>
<td></td>
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<td>.34</td>
</tr>
<tr>
<td>Total</td>
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<td>.78</td>
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Greenhouse Heat

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<th>Blower power:</th>
<th>Static air pressure (in W.G.)</th>
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<td>Air flow</td>
<td>1400 cfm</td>
<td>550 watts</td>
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</tr>
<tr>
<td>Blower power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock box and filter distribution</td>
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<td></td>
<td>.29</td>
</tr>
<tr>
<td>Distribution</td>
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<td></td>
<td>.16</td>
</tr>
<tr>
<td>Total (external to furnace)</td>
<td></td>
<td></td>
<td>.45</td>
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Residence Heat

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<th>Static air pressure (in W.G.)</th>
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<td>Air flow</td>
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<td>340 watts</td>
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<tr>
<td>Blower power</td>
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<td>Rock box and filter</td>
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<td>.21</td>
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<tr>
<td>Total (external to furnace)</td>
<td></td>
<td></td>
<td>.34</td>
</tr>
</tbody>
</table>
with 86 cubic feet (2.4 cubic meters) of excess. This was added to accommodate the storage of greenhouse solar radiation.

AIR DUCT DESIGN

Solar air systems depend heavily upon good quality ducts and dampers to assure that most of the collected heat reaches the heated space when required. From the thermal standpoint, ducts must be sealed against leakage and must be insulated where hot air is conveyed. This is accomplished by taping all duct seams so that air cannot leak in or out. This is not a difficult or costly task, but is simply not done on conventional residential ductwork. The insulation should be one inch thick or have an R value of at least 4 ft²·°F·hr/Btu. This can be applied as a duct lining or by using high density fiberglass duct board.

The fiberglass duct board was selected for use in the CSU project. It is less expensive than lined sheet metal and requires fewer mechanical skills and tools. Duct board is not as strong as metal duct, and thus should not be employed where heavy traffic or other factors might cause it to be damaged. Duct sizing is done using conventional methods for good duct design. The ducts are large enough to minimize pressure loss and noise, but not oversized, which would increase the cost unreasonably and consume excess space. The ducts were sized for a maximum of 700 feet per minute (3.55 meters per second) air velocity. Also, turning vanes were used in all ducts greater than 12 inches (30.5 cm).

Dampers were used which have compressive rubber seals. They are specified to have five percent leakage at two inches of static pressure. The dampers are operated by conventional 24 volt electric damper motors. An important consideration is to provide access openings next to the dampers. This is to make adjustments and to inspect the dampers for leakage or any mechanical problems.

Blowers are standard commercial products, sized for the system by conventional engineering practice for cfm, static pressure, speed, and power considerations. Belt-driven blowers are preferred over direct drivers because fine speed changes can be made by simple pulley adjustments. Blower speeds above 1000 rpm should be avoided because of noise considerations.

The blowers for space heating of both the residence and greenhouse were provided in the auxiliary forced air furnace. This was convenient because the blowers were preassembled and installed.

SYSTEM OPERATION

The solar system went into operation on December 10, 1976. The month of December was devoted to system testing and balancing. The data measurement system was installed during December and the first two weeks of January. A few days were required to verify measurements by making an
energy balance of the storage unit. This was simply to confirm that the energy delivered to the rock box equaled that removed from the box over a period of four or more days. When this was accomplished, the official data monitoring period began, which was January 23, 1977.

Data have been processed for January and February for entry into this report. Results for this period are presented as bar charts in Figures 10 through 12. For the period January 23 to February 20, 1977, 84 percent of the heating requirement of the combined residence and greenhouse was met by solar energy. Of this solar heat recovery, 87 percent was derived from solar collectors and 13 percent was obtained from the greenhouse.

It is important to note that, on several days, the greenhouse reached 90°F (32°C) while solar heat was being collected. At that point, the greenhouse was ventilated to avoid high temperature stress to the plants. Available solar heat was thus lost because the air flow was insufficient to collect the heat below 90°F. Also, there is warm air returning from the rock box to the greenhouse on days when large quantities of heat are collected. This indicates that more energy could be stored from the greenhouse if the air flow was increased or if the rock box were deeper. The penalty, however, is in additional blower power.

Electrical power was measured during the February operation and compared with solar heat delivered to the building. This is the electrical power required to operate the collector blower plus the portion of the greenhouse and house heating blower power to deliver solar heat. That quantity of power was 4.8 percent of the delivered solar heat.

Blower power is a function of the volumetric air flow rate and the static pressure of the system. Table 2 lists the static air pressure distribution for the three air circuits.

CONCLUSION

Solar heating can be applied effectively to supply a major fraction of the heating demand for a greenhouse or greenhouse/residence combination. A well-constructed greenhouse is considered basic to such a solar application. This is because economics do not favor a large solar system to meet the demands of a high heat loss structure. Also, the tightly constructed greenhouse becomes a low temperature solar collector to be employed with or without additional solar collectors for the capture of solar heat. The degree to which the greenhouse can contribute useful solar heat depends upon climatic conditions and the upper temperature limit in the greenhouse.

The Colorado State University Solar greenhouse/residence project has demonstrated that a solar heating capability of 87 percent is obtainable during a winter heating period using commercially available equipment and conventional (or easily developed) construction methods. Combining a greenhouse with a solid wall space heated structure offers some heating advantage. This results from heat loss reduction and overall solar
Figure 10.

HEAT SUPPLY AND DEMAND
JAN. 23-31, 1977

$10^6$ BTU'S

<table>
<thead>
<tr>
<th></th>
<th>SOLAR COLLECTION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>COLLECTORS</td>
<td>3.06 (84%)</td>
<td>GREENHOUSE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SOLAR HEAT DELIVERED</th>
<th>FUEL HEAT DELIVERED</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.66 (82%)</td>
<td>0.8 (18%)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 11.
HEAT SUPPLY AND DEMAND
FEB. 1-20, 1977

$10^6$ BTU'S

0 1 2 3 4 5 6 7 8

SOLAR COLLECTION
COLLECTORS, 5.5 (88%)
GREENHOUSE, 0.6 (12%)

SOLAR HEAT DELIVERED, 6.1 (85%)
FUEL HEAT DELIVERED 1.1 (15%)

ELECTRICITY FOR SOLAR
0.293 (4.8%)
Figure 12.

SOLAR COLLECTION
FEB. 1 - 20, 1977

$10^6$ BTU's

- SOLAR RADIATION ON COLLECTOR 13.2
- COLLECTED IN COLLECTORS 5.5 (42 %)
- SOLAR RADIATION ON GREENHOUSE 13.2
- COLLECTED IN GREENHOUSE 0.6 (5 %)
system performance. This influence of combined structures is not seen to be size dependent, and should be valid for larger scale installations.

The operation of the greenhouse and of the residence or other heated space is not altered by the application of solar heat. The heating and cooling functions may be totally automated with human attendance comparable to conventional fuel energized systems.

Air as the heat transfer fluid offers some dependability advantage. Boiling, freezing, corrosion, and damage from leaks are some conditions avoided with the use of air.

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REFERENCES