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THE RUTGERS SOLAR HEATING SYSTEM FOR GREENHOUSES

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SUMMARY: A low-cost system for heating greenhouses with solar energy has been developed at Rutgers. The collector, heat saving curtain, heat exchangers, porous concrete-capped floor storage and total system performance through the 1976-77 winter heating season are discussed. An economic evaluation of the system indicates that the use of solar energy for heating greenhouses can be cost-effective at today's fuel prices.

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The Rutgers Solar Heating System for Greenhouses

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INTRODUCTION

Research on solar heating of greenhouses at Rutgers has been geared to applications with commercial, double-covered polyethylene structures. Emphasis has been placed on the development of relatively low-cost systems in order to have an economically feasible alternative to fossil fuel for greenhouse heating as soon as possible. The materials and construction techniques being utilized are currently available in the greenhouse industry. The performance of the system from September 1, 1976 through May 3, 1977 is presented. Based upon experience to date some estimates are made regarding the economic potential of the entire system based on current prices.

The Rutgers integrated solar assisted greenhouse heating system was first presented by Roberts et al. in 1976. This system consists of four major elements, all of which are necessary for maximum conservation of fossil fuel: a low-cost external plastic solar collector, a movable curtain insulation system, a porous concrete-capped storage/heat exchanger composite floor and vertical curtain heat exchangers. A fossil-fuel-fired backup unit provides heat to the greenhouse when the solar energy in storage has been depleted.

LOW-COST PLASTIC SOLAR COLLECTOR

The solar collector consists basically of a frame covered with five layers (two clear tubes and a black sheet) of plastic film. The black plastic sheet, which is the absorber plate of the collector, is sandwiched between the two air-inflated clear greenhouse grade polyethylene tubes. The air spaces between the bottom two layers and the top two layers are kept inflated with small blowers. The absorber plate is pressed between the two inflated polyethylene cushions providing stabilization of the structure and some insulation

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due to the trapped dead air spaces. The frame is 4 m (13 ft) high, with rafters on 1.2 m (4 ft) centers. This design utilizes 4.3 m (14 ft) rolls of lay-flat polyethylene tubing in any standard length. Water is introduced along the top of the collector through a perforated header pipe and flows over the black absorbing layer. A gutter at the bottom of the frame collects the heated water. The collector orientation is south and the slope is adjustable between 25^o and 65^o to compensate for seasonal changes in the sun angle above the horizon. Some of the early prototype collectors were constructed using a rigid plywood back to facilitate the addition of rear insulation (Mears and Baird 1976 and Mears _et al_. 1977). The method of collector comparison used was a side by side test of two units to determine the differences in performance. For both units, heat collection rates were measured by the suggested standard method of Hill and Kusuda (1974). Solar incidence on the plane parallel to the collector was measured during the test.

A collector being built for the 1977-78 heating season, a slight modification of the one described previously, is shown in Fig. 1. Instead of five plastic layers, it will have four, two black and two clear. The black layers will not be replaced as often as the clear ones, so a separate fastening system will be used for each tube. The metal frame is being built with commercial greenhouse components.

In interpreting the data from the collector tests, it is helpful to consider the following simplified relations for the energy balance on the collector:

$$Q_c = CQ_s - U_L (T_c - T_a)$$

The useful energy collected, Q_c, is the difference between the energy absorbed by the collector plate, CQ_s, and the heat losses from the collector, $U_L (T_c - T_a)$. The available incident solar energy on the plane of the collector is Q_s and the constant C is the product of the overall transmissivity of the covers and the absorptance of the collector plate. The constant U_L is the overall heat loss coefficient for the collector, the temperature T_c is the average temperature of the water flowing through the collector and T_a is the temperature of the surroundings. Defining efficiency, E as:

$$E = \frac{Q_c}{Q_s} = C - U_L \frac{T_c - T_a}{Q_s}$$

a very useful expression for evaluating the collector is obtained. In the experiments, the parameters Q_c, Q_s, T_c, and T_a are measured for each test. Computing E directly from the ratio Q_c/Q_s and also computing the ratio of the temperature difference $(T_c - T_a)$ to incident solar energy Q_s for each test enables one to graph efficiency E vs. the normalized temperature elevation of the working fluid $(T_c - T_a)/Q_s$. When a number of points are plotted, a straight line can be fitted to the data and the constants C and U_L determined.

Previous reports have covered the effects of certain construction and operation options on the performance of the collectors (Mears et al. 1976 and Mears et al. 1977). Variables tested included the use of a wetting agent, varying water flow rate, shadecloth mesh over the black absorber to promote surface wetting and the use of insulation on the collector back. It has been found that complete wetting of the absorber surface is an important requirement for achieving maximum efficiency. Incomplete wetting of the absorber surface lowers the collector's performance as does a nonuniform flow. The addition of a shade cloth netting, use of a detergent and maintenance of adequate water flow all contribute to efficiency. The results of some recent collector tests are presented in the performance table. Unit A was used as a comparison standard and consisted of clear polyethylene tubes front and back with an unmodified black polyethylene layer as the absorber plate. Unit B used a single black tube in the back, a clear tube in the front and no extra absorbing layer. Surface wetting was slightly improved as signified by the increase in the constant C from 0.74 to 0.79 and the heat loss was unaffected as there is no change in U_L. Unit C was like Unit A except a polypropylene mesh was inserted over the absorber to spread water more uniformly. The effect of this addition is to increase the wetted area as indicated by the increase in C to 0.84. This is a significant improvement. In Unit D an aluminized layer was slipped in between the absorber plate and the back inflated cushion to add some reflective insulation. The effect was a 10% reduction in the heat loss coefficient U_L with no significant change in C. The efficiency curve for Unit C is given in Fig. 2.

Reducing heat loss from the collector improves collection efficiency, especially at higher water temperatures or lower outside air temperatures. Increasing the wettability of the surface by the use of the mesh or other methods, reduces the water flow needed to maximize the constant C, which is the most important factor for a collector operating at low temperature. Lowered water flow rates save on pumping power and the size of plumbing required.

PERFORMANCE OF SOME OF THE COLLECTORS TESTED

			U_L	
Unit	Collector Modification	C	$\frac{BTUh}{ft^2\,{}^oF}$	$\frac{W}{m^2K}$
A	None	.74	-2.7	-15
B	Rear Black Tube	.79	-2.7	-15
C	Shadecloth over Absorber	.84	-2.7	-15
D	Absorber Back Aluminized	.79	-2.4	-13.3

In addition to these performance tests, some efforts were made to discover the problems that would be encountered in practical applications of these units. In general, all of the rules and recommendations pertaining to greenhouses covered with two air-separated layers of polyethylene apply. Also, there can be a problem if the collector is in full sun and not cooled by the water. Maximum temperatures of the black plastic layer can reach 85°C (185°F). At these temperatures, the black polyethylene becomes very soft and the inner clear cover can stick to it permanently. Also, if the clear plastic rests directly on the black at the edges of the collector, it will become brittle and fail rapidly at that point. To overcome these problems, it is best to build the collector so that there is a framework around all the edges between the black absorber and the clear cover which can be painted white.

MOVABLE CURTAIN INSULATION SYSTEM

Double-covered polyethylene greenhouses require two-thirds the heat of similar size and shape single glazed structures, but further heat loss reduction is needed if solar heating is to become practical. Curtain insulation systems to reduce heat loss are now being utilized with conventional heating systems and several companies are marketing systems.

Simpkins _et al_. (1976) reported that a properly installed thin film curtain system could save up to half of the heat requirement of a double-layer air-inflated polyethylene greenhouse. Rebuck _et al_. (1976) reported a 50% heat savings when using a thin film curtain in a single-layer glass greenhouse as did Bailey (1975).

Substantial heat savings are obtained with properly installed single-layer thin-film curtains. If the following recommendations for curtain installation are followed, approximately half of the heat requirement of a double-layer air-inflated multibay polyethylene greenhouse can be saved using an infrared radiation reflecting curtain material. The curtain should be fastened horizontally eave to eave in a single bay greenhouse and gutter to gutter in a multibay one. It is important to have an airtight seal along the curtain edges. The tightness of the curtain against air infiltration is the primary heat savings factor and the infrared radiation properties of the curtain material are the next most important.

As a first measure, installing a curtain system is more important than the radiation properties of the curtain material. Any nonporous thin film will provide the conduction-convection savings of the two air film resistances and the trapped air space, which should result in at least a 25% fuel savings. Movable clear polyethylene film should not be used in plastic greenhouses because it provides little infrared radiation benefits. The temptation to install a permanent polyethylene horizontal liner in a glass greenhouse is to be avoided. Structural stability in snow areas is threatened and the light reaching the plant canopy is significantly diminished in the winter. Physical properties of the curtain material, folding (to minimize crop shading when the curtain is stored during the day), tear strength, durability, U.V. light resistance, weight, expected life, etc. must be considered along with the cost when choosing the material to be used for the curtain.

Mechanical systems of all types are used to position or close the curtains during the night. The curtains, of course, must be stored in the daytime to minimize shading of the growing crops. Roberts (1970) reported on one system which hangs the curtain from cables. A method for installing a curtain system is given in Fig. 3.

POROUS CONCRETE-CAPPED COMPOSITE FLOOR

The porous concrete floor system is both storage and primary heat exchanger for the greenhouse. The floor is constructed of four layers: polystyrene board insulation, a vinyl swimming pool liner, gravel, which will be flooded with water and a cap of porous concrete. The porous concrete forms a firm floor, a heat exchange surface and allows excess irrigation water to drain. The water provides thermal storage when mixed with the gravel and is the heat transfer fluid for the solar collector and secondary heat transfer system. The vinyl liner contains the concrete, gravel and water. The insulation also serves as mechanical protection for the liner during construction. Details of the floor are shown in Fig. 4.

The porous concrete is made with aggregate, cement and water but no sand. The formula is 1660 kg of 0.95 cm aggregate, 7.8 bags of cement and 100 to 125 liters of water per cubic meter of mix (2800 lb of 3/8 in. aggregate, 6 bags of cement and 20 to 25 gallons of water per cubic yard). Tests at Penn State (Aldrich, 1977) indicate this mix has a compressive strength of 3.4 to 4.1 M Pa (500-600 psi). There are several advantages to the grower: no weeds can grow in the house and carts can be used over the entire floor area for those who grow on the floor. Perhaps the greatest advantage is that when using automatic irrigation or misting systems the excess water drains through the floor. Normally with an impervious floor, low spots occur and plants are suffocated by the water which accumulates in these low areas. Freeze-thaw tests at Penn State indicate that this concrete is not suitable for outdoor use.

The void ratio of the gravel is 50%, so a cubic meter of gravel weighs about 1680 kg (105 lb/ft^3) and contains approximately 512 kg of water (32 lb/ft^3). The total heat storage capability of the water-gravel mixture is 3550 $J/m^3 \cdot K$ (53 $BTU/^{\circ}F \cdot ft^3$).

The heat transfer rate from floor storage to the greenhouse growing area has been determined over a range of operating conditions. The average rate is 8.23 W/m^2K (1.45 $BTUh/ft^2 {}^{\circ}F$) but it varies with water depth in the storage and temperature difference between the storage and greenhouse air temperature. Average conditions are: storage temperature 23.9-26.7°C (75-80°F), air temperature 15.6-18.3°C (60-65°F) and water level at the bottom surface of the porous concrete cap.

HEAT EXCHANGERS

In an evaluation of one of the first greenhouse solar heating systems Baird and Mears (1976) showed that under normal operating conditions, storage temperatures generally ranged within 5 to 15K (10 to 30°F) of the greenhouse night temperature setting. Energy collected during the day will normally be utilized at night in a well designed solar system. Maintaining the temperature of solar energy storage at the lowest possible level significantly improves the performance of the solar collector since collection efficiency decreases with increasing operating temperature for all flat plate collectors. Low storage temperature allows inexpensive collectors to be used but requires that a large area of inexpensive heat exchanger be provided so heat can be extracted from the low temperature water effectively. This is the function of the vertical curtain heat exchangers which are made by connecting a trickle irrigation hose to a horizontal support. A plastic film is draped over this support like a bed sheet over a clothesline. The support is attached to cables so that the exchanger can be elevated at night and lowered to the floor during the day. The curtain would normally be positioned along a row of poles to minimize interference with cultural operations. The support is near the eave line when elevated and both edges of the plastic curtain touch the floor. When heat is needed a thermostat actuates a pump which circulates warm water from the floor through the trickle irrigation hose. As the water leaves this hose and trickles down between the hanging curtains the entire inside surface is wet. The water exits the bottom of the curtain and returns directly to storage through the porous concrete. The unit could be used with a return gutter at the bottom.

The composite floor is the primary heat exchanger and the vertical curtains are secondary. The vertical curtain heat exchangers are shown in Fig. 5.

The design water flow rate is 0.035 l/s·m (0.15 gpm per ft) of header. The water in the floor storage ranges from 7 to 14K(12 to 25°F) above the air temperature in the test greenhouse under normal operating conditions. When this difference falls to 7 K (12°F) a backup oil burner can be actuated to provide additional heat through a heat exchanger pipe loop in the gravel/water composite floor (Fig. 4). The greenhouse was maintained at 16°C (60°F) by the heat transferred from the floor surface and the curtain heat exchangers. When outside air temperature was above 5°C (41°F) the heat transfer from the floor area alone was sufficient to maintain the set temperature. A thermostat activated the pump supplying water to the vertical curtain exchangers. Usually the vertical curtain heat exchanger pump would cycle, but under the coldest conditions it ran continuously. When the vertical curtain heat exchangers are operating continuously, the weighted average heat transfer rate from floor storage to the greenhouse through both the floor surface and the vertical curtain exchangers is 8.69 W/m^2K (1.53 $BTUh/ft^2{}^oF$).

Preliminary tests on curtains of polyvinylchloride and polyethylene indicate there is no significant difference in heat transfer performance. The vinyl material folds more compactly when the curtain is lowered to the floor. Further research is underway to improve the performance and reduce the operating costs of the curtain heat exchangers. It is expected that treatment of the inner surfaces of the film will enhance wetting, enabling lower water flow rates to be utilized. Also, a more uniform water distribution system is needed to reduce the required pumping horsepower. Even though pump horsepower costs less than 5 percent of the value of the heat being transferred, further reductions in electrical consumption would be helpful. A major requirement for commercial adaptation of these units is that they be located out of the way of cultural operations in the greenhouse. An experiment is currently underway in which some clear curtains are permanently installed over the center of a split trough with one row of tomato plants growing on each side of the unit. In this heating system all heat, solar and fossil fuel backup, is delivered to the greenhouse through the combination of the warm floor and vertical curtain heat exchanger. A two-stage thermostat can be used for heating systems control. The first stage turns on the pump for the vertical curtain heat exchangers on temperature fall. If the greenhouse air temperature continues to fall, the second stage will turn on the circulator pump of the backup heating system.

The heat exchange system for the backup heat supply in the test greenhouse involved 2.5 cm (1 in.) diameter polyethylene pipe buried in the gravel-water floor storage. The heat transfer rate averaged about 163 W/m of pipe (170 BTUh/ft of pipe) with 22.2 K (40^oF) temperature difference between the water in the pipe and the storage. Comparable heat transfer rates were obtained with 2 cm (3/4 in.) thin wall polyethylene pipe while 2 cm steel pipe was found to transfer heat at about 2.7 times the rate of the plastic pipes. Another system for adding fossil fuel heat to storage would be the use of a tube and shell heat exchanger. The water in storage would be pumped to the exchanger where it would be heated and then returned to storage, much in the same manner as it flows through the collector. This has the advantages of saving labor and time during floor construction and keeping the heat exchanger easily accessible.

SYSTEM PERFORMANCE THROUGH THE WINTER OF 1976-77

A greenhouse and solar collector system using the components described was tested from September 1, 1976 through May 3, 1977. The test greenhouse and solar collector are shown in Fig. 6. The pattern of water flow from the greenhouse floor storage through the solar collector and back is shown in the schematic of Fig. 7. The greenhouse is nominally 5.2 m by 7.3 m (17 ft by 24 ft). The useful floor area in the greenhouse is 33.4 m^2 (360 ft^2) and the exposed roof and wall area is 79.9 m^2 (860 ft^2). The face area of the collector is 33.8 m^2 (364 ft^2). The greenhouse interior is shown in Fig. 8. The two center vertical curtain heat exchangers were not used and have been removed. The exposed heat transfer area of the two vertical curtain heat exchangers is 37.2 m^2 (400 ft^2). The system has been run continuously on automatic control and the performance of each component has been monitored.

The insulating curtain of black polyethylene has proven effective in reducing heat loss from the greenhouse. The heat loss coefficient from the entire building has averaged 2.55 W/m^2K (0.45 $BTUh/ft^2 {}^oF$) based on the total exposed roof and wall area. Without the curtain the heat loss rate from this building is 4.54 W/m^2K (0.80 $BTUh/ft^2 {}^oF$). A fringe benefit of the entire warm floor system is its ability to carry a crop safely through a component failure during cold weather. One night the fuel oil line to the burner froze and the outside temperature fell below -18^{o}C (0^{o}F). The floor storage fell to 17.2^{o}C (63^{o}F) and the greenhouse temperature dropped to 11.1^{o}C (52^{o}F), but there was no damage to the tomato crop. For two nights there was no fossil fuel backup due to a fault in the oil burner. The outside temperatures were -14.4^{o}C (6^{o}F) the first night and -6.7^{o}C (20^{o}F) the second. This time the system ran on solar energy alone and again the crop was maintained safely at 9^{o}C (49^{o}F). The insulating curtain and the large thermal mass of the floor provide a significant carrying capacity in the event of power outage or other temporary component failure.

The energy budget of the entire system as operated during the heating season is presented in Table 1 and Fig. 9. The data is presented for each week through May 3, 1977.

The weekly totals on degree days indicate the unusual severity of the past winter. In Table 1, energy used has been converted to the equivalent in liters of fuel oil for the entire greenhouse at the rate of 1 liter for each 27.87 MJ (100,000 BTU/gal) and the solar energy noted is only that required to provide the needed heat. Excess solar energy was collected during the fall and again in the spring. Over the entire period solar energy provided 53% of the total energy required.

For economic evaluation it is important to know the total fuel requirement per unit floor area of each of several greenhouse systems. The data collected thus far has been used to produce the calculated results shown in Table 2 and Fig. 10. The projections are based on the actual performance of the solar system this past winter in which the degree days accumulated through February were about equal to the total for a normal winter. The first column of Table 2 shows the predicted weekly fuel oil use in the greenhouse if it were single glazed with a heat transfer coefficient of 6.81 W/m^2K (1.2 $BTUh/ft^2 {}^oF$). The total of 3880.7 liters (1025 gallons) of fuel works out to 116.2/m^2 liters (2.85 gallons/ft^2) of floor area. The second column gives the fuel requirement for the same size house with double polyethylene cover but no insulation or solar heat input. The total of 2587 liters (683 gallons) is 77.5 liters/m^2 (1.90 gallons/ft^2) of floor. Table 1 showed that the insulation curtain reduced the total requirement to 1455 liters (384 gallons) or 43.6 liters/m^2 (1.07 gallons/ft^2) of floor. The solar system provided 23.0 liters/m^2 (0.56 gallons/ft^2) and the fossil fuel system 20.6 liters/m^2 (0.51 gallons/ft^2) of floor. These figures indicate a 56.9 liters/m^2 (1.39 gallons/ft^2) fuel savings for the Rutgers system over the conventional test double-polyethylene-covered greenhouse.

Size of the greenhouse is very important and a multibay gutter-connected greenhouse of an acre or more would have one-half the exposed roof and wall area compared to floor area of the small test greenhouse. The data in the last two columns of Table 2 are based on an equivalent floor area as the test unit which is included in a large, multibay gutter-connected greenhouse. The total heat requirement per unit area is one-half that actually achieved in the test facility and is 21.8 liters/m^2 (0.53 gallons/ft^2) of floor. If the same floor and storage system were used and the ratio of solar collector area to floor area were kept at 1 to 1, the solar contribution could be expected to remain the same. The resulting predicted fossil fuel requirement in the last column of Table 2 totals 3.85 liters/m^2 (0.09 gallons/ft^2) of floor area.

Actual operation of the small test house has indicated that increased storage is desirable. The floor storage of additional units now under construction have had the gravel depth increased to 23 cm (9 in.) in a 11 m by 14.6 m (36 ft by 48 ft) greenhouse and to 30 cm (12 in.) in a 11 m by 30.5 m (36 ft by 100 ft) greenhouse. Substantial storage increases can be obtained at relatively low cost as the only added cost of storage is the incremental cost of the extra stone and liner being used.

The contribution of the solar collector to the system is given in the fourth column of Table 1. The instantaneous efficiency characteristics of the collector have been presented (Roberts et al. 1976). The efficiency at any time depends upon insolation and the relative temperatures of the water and the outdoor ambient air. Analysis of data collected thus far indicates that with the temperatures usually encountered, collector efficiency ranges between 40% and 60% on clear days with the higher efficiencies occurring on warmer days. On the coldest days efficiency was about 35%. Low storage temperature is the most important factor in maintaining collection efficiency and this is another reason for increasing storage capacity.

A crop of trough culture tomatoes was planted in the fall in the test facility and floor temperatures were deliberately elevated to determine the effects of the warm floor heating system on plants. No adverse effects on the tomatoes were noted for temporary floor temperature as high as 47.8°C (118°F) and soil temperatures of 42.2°C (108°F). The soil mix of 50% peat moss/50% vermiculite has a 90% voids ratio. It is presumed that good root aeration overcame any deleterious effects of high soil temperature. In spite of some rough horticultural treatment, the yield was 2.7 kg (6 lb) of fruit per plant and larger than normal individual fruit size was noted. A spring tomato crop and several varieties of bedding plants are being grown directly on the floor at present.

ECONOMIC PROJECTIONS

Predictions of economic feasibility of the complete system are difficult to make objectively and are very sensitive to assumptions. Of particular importance is the initial heat requirement of the greenhouse to be solarized. Dramatic fuel savings are predicted when an energy inefficient greenhouse is selected for comparison. In this discussion the standard reference is a gutter-connected, double-covered polyethylene greenhouse of at least one acre in size. This is a very energy-efficient structure by current standards and should require about 40.75 liters/m^2 (1.0 gallon/ft^2) of fuel oil for a heating season resembling that profiled in Table 2.

Construction of a floor system with 23 cm (9 in.) of storage and a collector area equal to floor area should result in a reduction of fossil fuel heating requirement to 3.9 liters/m^2 (0.1 gallon/ft^2) for the same heating season. At 13.2¢ per liter (50¢ per gallon) for fuel oil, this would be a savings of $4.85 per square meter (45¢/ft^2) per year. The material costs per square meter of floor for building the complete system have been estimated as follows:

for the insulation, liner, rock, heat transfer loop and concrete in the floor, $10.25; for the heat conserving curtain system, $2.15; for the vertical curtain heat exchangers, $0.55; for the solar collector $5.40 and for pumps, piping and controls, $1.10: for a total of $19.45. The annual cost of recovering the collector would be $0.55.

Based upon the above the complete system would save $4.30/m^2 per year to be applied to the amortization of the initial cost which would be $38.90/m^2 if labor were equal to materials. Labor is the most difficult cost to estimate as such a system has not been installed on a large scale. There would be one or two important items to consider that would reduce the relative cost of the solar heating system for new construction. First would be a credit for the cost of the conventional heating system. If an overhead pipe system with hot water were being replaced, the overhead pipe which costs about $10.75 per square meter for materials would be saved. The oil burner for the backup in the solar heating system would be smaller than that in a conventional system so the costs of these units would at least cancel. The extra cost for the materials for the solar heating system would be reduced to $8.60 per square meter in this case and the economic comparison is much more favorable. An additional $2.70 per square meter in the differential cost would be eliminated if a porous concrete floor were to be installed in either case. The use of a warm porous concrete floor could allow crops to be grown on the floor in some cases, thereby saving the cost of benches.

A complete retrofit, where conventional heating system, benches and other items are in place is not economical based on current fuel prices. However, if savings on floor or benches and on conventional heating systems can be applied to construction of the solar heating system, then the economic feasibility of the system is greatly enhanced. The entire system can be amortized in a few years under the most favorable circumstances. The reduction in total heat requirement due to the curtain insulation system is the most significant factor in the cost effectiveness of the system and is recommended for most greenhouses. The comparison is more favorable on a relatively less energy efficient greenhouse, such as the unit actually tested. The actual total fuel savings due to the insulation and solar heating system amounted to 56.9 liters of fuel per square meter of greenhouse for a savings of $7.50 per year; $6.95 after subtracting the collector recovering cost.

FURTHER WORK

The system needs to be tested on a larger scale under commercial operating conditions to determine crop response and to get more data on operating performance. No serious crop response problems are anticipated, but demonstration of compatibility of the heating system with various cultural practices is needed. System modifications will be required for crops that require different growing environments. Two existing greenhouses on the Rutgers campus are being retrofit for these studies and plans have been developed for a 670 m^2 (7200 ft^2) commercial demonstration project which could be operating next winter if all goes on schedule.

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References

1. Aldrich, R. A. 1977. Personal communication, Department of Agricultural Engineering, The Pennsylvania State University, University Park, Pennsylvania.

2. Bailey, B. J. 1975. Reducing glasshouse heat losses by internal blinds of different materials. NIAE, Wrest Park, Silsoe, Bedford, England. Departmental Note No. DN/G/617/2105.

3. Baird, C. D. And D. R. Mears. 1976. Performance of a greenhouse solar heating system. Proceedings of the Solar Energy-Fuel and Food Workshop, Environmental Research Laboratory, University of Arizona, Tucson, Arizona.

4. Hill, J. R. and J. Kusuda. 1974. Method of testing for rating solar collectors based on thermal performance. NBSIR 74-635, National Science Foundation, Washington, D. C., p. 60.

5. Mears, D. R. and C. D. Baird. 1976. Development of a low-cost solar heating system for greenhouses. Solar Energy - Fuel and Food Workshop, Environmental Research Laboratory. The University of Arizona, Tucson, Arizona.

6. Mears, D. R., W. J. Roberts and C. D. Baird. 1977. Performance of a low-cost plastic film solar water heater. Flat-plate Solar Collector Conference, ERDA, Orlando, Florida.

7. Rebuck, S. M., R. A. Aldrich and J. W. White. 1976. Internal curtains for energy conservation in greenhouses. ASAE Paper No. 76-4009, ASAE, St. Joseph, Michigan 49085.

8. Roberts, W. J., J. C. Simpkins and P. W. Kendall. 1976. Using solar energy to heat plastic film greenhouses. Solar Energy Fuel and Food Workshop, Environmental Research Laboratory, University of Arizona, Tucson, Arizona.

9. Roberts, W. J. 1970. Automatic black cloth shading for greenhouses. Biological and Agricultural Engineering Extension Paper, College of Agricultural and Environmental Science, Rutgers - The State University, New Brunswick, New Jersey.

10. Simpkins, J. C., D. R. Mears and W. J. Roberts. 1976. Reducing heat losses in polyethylene-covered greenhouses. Transactions of the ASAE (19)4.

Table 1

Actual Energy Use in Test Greenhouse in Equivalent Liters of Fuel Oil.

Week Beginning	Centigrade Degree Days	Total Energy Use	Energy from Solar	Energy from Fuel Oil
Sept. 1	8.9	5.5	5.5	
8	4.4	2.0	2.2	
15	0	0.6	0.6	
22	21.7	6.7	6.7	
29	30.0	8.4	8.4	
Oct. 6	29.4	7.5	7.5	
13	60.6	21.8	21.8	
20	68.3	39.4	39.4	
27	91.1	34.6	34.0	0.6
Nov. 3	87.2	47.5	30.0	17.5
10	109.5	53.8	32.3	21.5
17	98.3	46.0	30.7	15.3
24	100.6	50.9	23.8	27.1
Dec. 1	152.2	72.6	23.5	49.1
8	130.6	66.7	22.1	44.6
15	118.9	61.7	14.5	47.2
22	150.0	70.5	34.1	36.4
29	173.7	73.9	32.8	41.1
Jan. 5	153.3	75.3	12.4	62.9
12	196.7	84.4	22.7	61.7
19	180.6	72.2	33.6	38.6
26	177.8	71.0	39.2	31.8
Feb. 2	157.8	74.1	26.3	47.8
9	115.6	58.4	17.3	41.1
16	149.5	63.5	27.7	35.8
23	82.2	47.3	32.8	14.5
Mar. 2	87.2	41.7	13.5	28.2
9	50.0	18.8	18.8	
16	89.5	43.0	34.7	8.3
23	94.5	46.1	29.6	16.5
30	38.9	15.4	15.4	
Apr. 6	86.1	41.0	41.0	
13	25.0	6.8	6.8	
20	19.4	9.9	9.9	
27	43.3	15.7	15.7	
TOTAL	3182.8	1454.7	767.3	687.6

Table 2

Predicted Energy Use for Equal Floor Areas in Equivalent Liters of Fuel Oil.

Week Beginning	No Insulation Single Glaze	No Insulation Double Poly	Total Use in Large House	Fossil Fuel Use in Large House
Sept. 1	14.8	9.8	2.8	
8	5.2	3.5	1.0	
15	1.7	1.1	0.3	
22	18.0	12.0	3.4	
29	22.4	14.9	4.2	
Oct. 6	20.0	13.3	3.7	
13	58.3	38.9	10.9	
20	105.1	70.1	19.7	
27	92.4	61.6	17.3	
Nov. 3	126.7	84.5	23.8	
10	143.5	95.6	26.9	
17	122.7	81.8	23.0	
24	135.8	90.5	25.4	1.6
Dec. 1	193.6	129.1	36.3	12.8
8	177.8	118.5	33.3	11.3
15	164.8	109.8	30.9	16.4
22	188.2	125.5	35.3	1.1
29	197.2	131.5	36.9	4.2
Jan. 5	200.8	133.8	37.6	25.3
12	224.9	149.9	42.2	19.5
19	192.7	128.5	36.1	2.5
26	189.3	126.2	35.5	
Feb. 2	197.8	131.9	37.1	10.7
9	155.8	103.9	29.2	11.9
16	169.6	113.0	31.8	4.0
23	126.0	84.0	23.6	
Mar. 2	111.1	74.1	20.8	7.4
9	50.1	33.4	9.4	
16	114.7	76.5	21.5	
23	122.9	81.9	23.1	
30	41.0	27.3	7.7	
Apr. 6	109.3	72.9	20.5	
13	18.2	12.1	3.4	
20	26.4	17.6	5.0	
27	41.9	27.9	7.8	
TOTAL	3880.7	2586.9	727.4	128.7

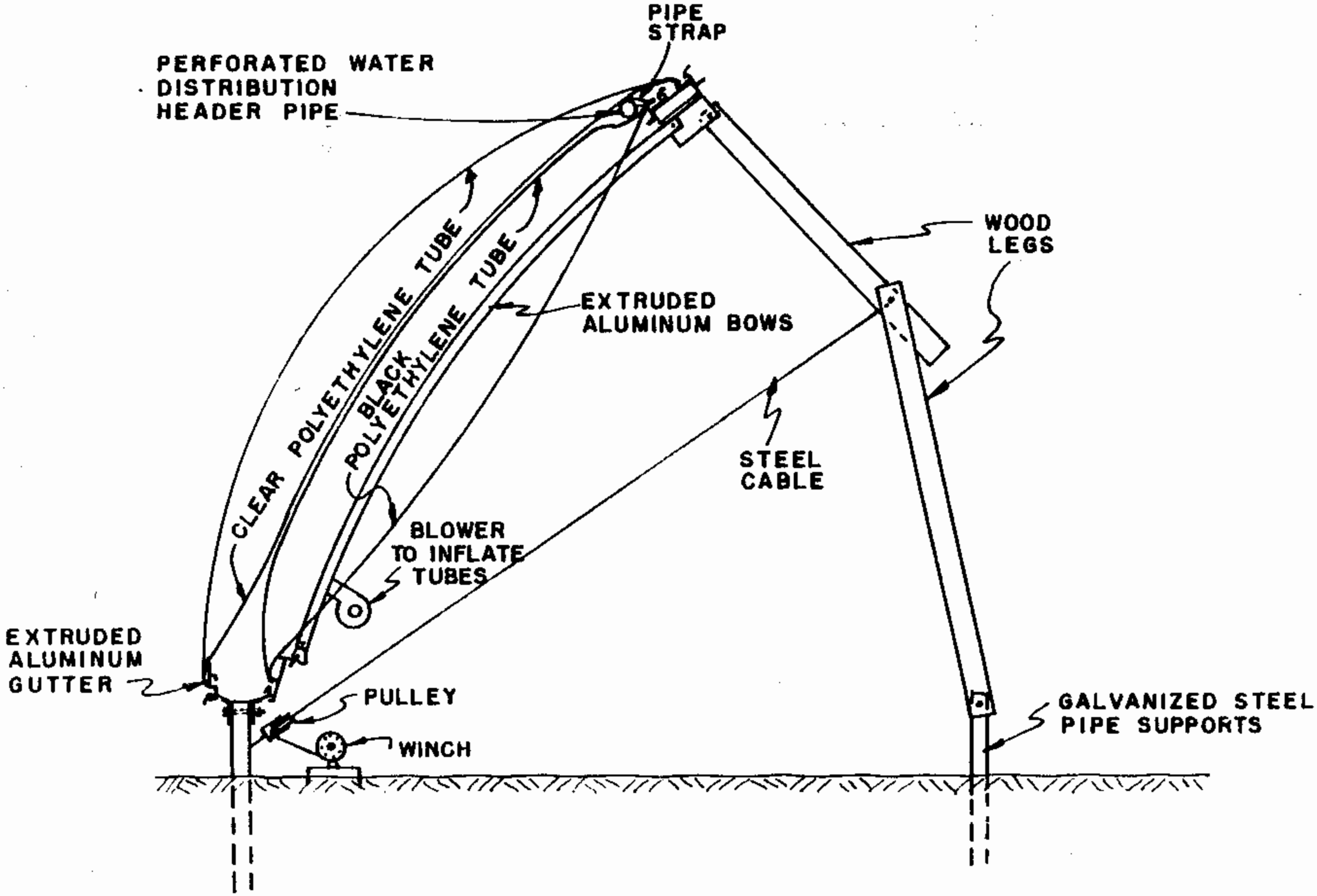


FIG. - I CROSS SECTION OF 4 m x 29 m RUTGERS ADJUSTABLE SLOPE POLYETHYLENE SOLAR COLLECTOR

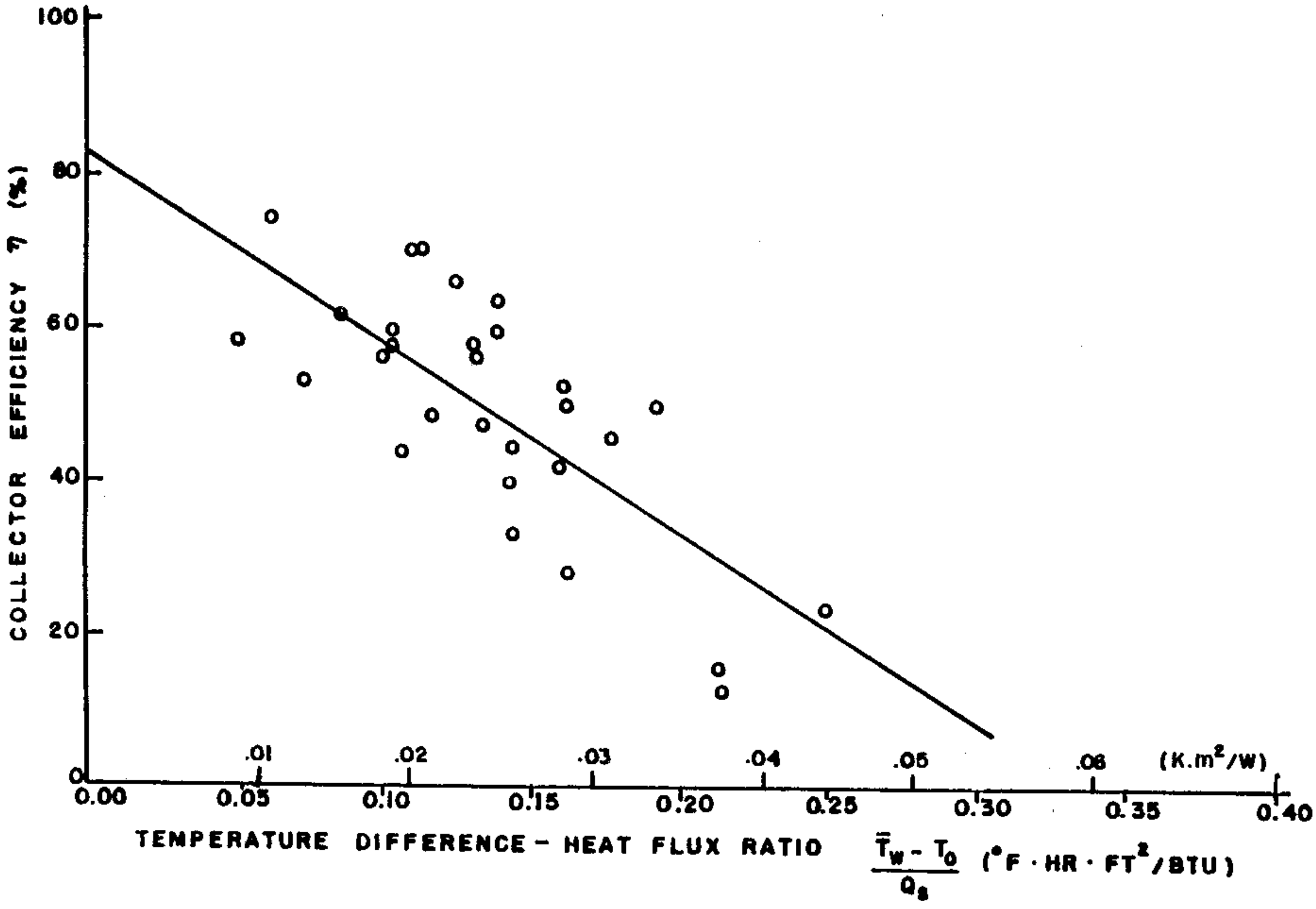
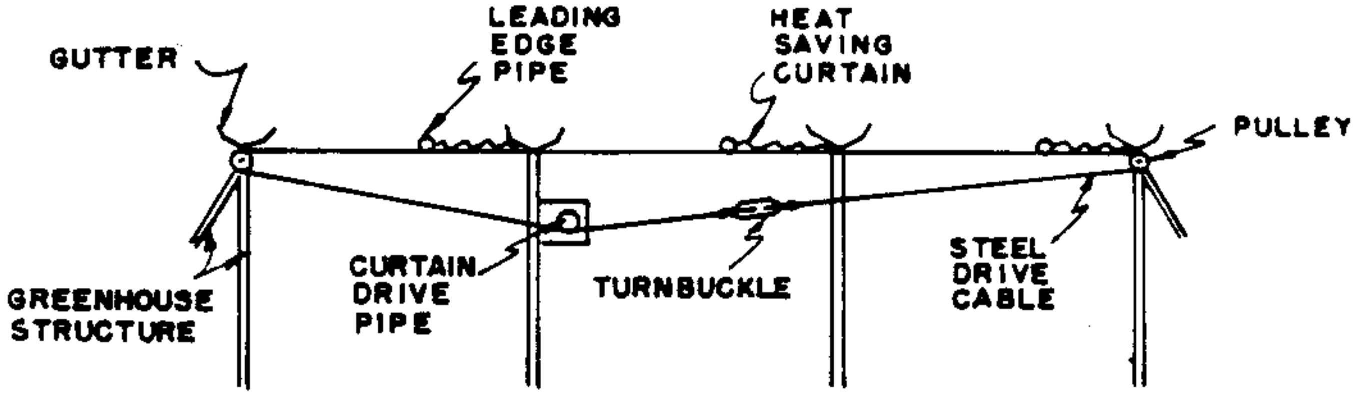
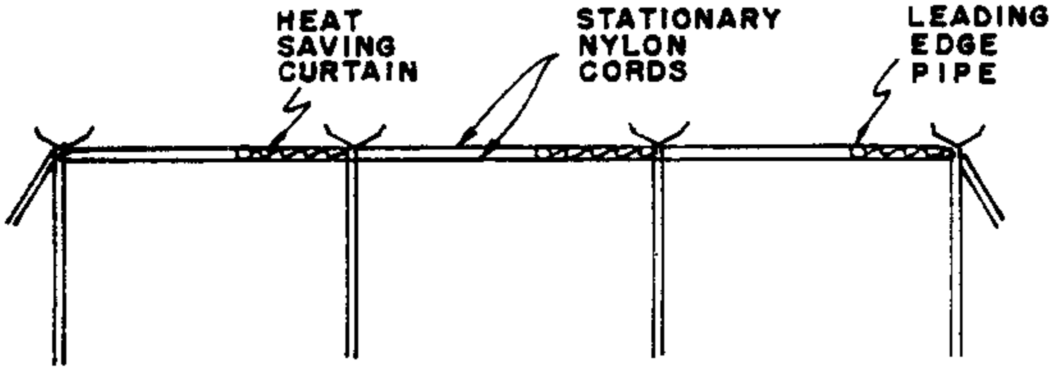


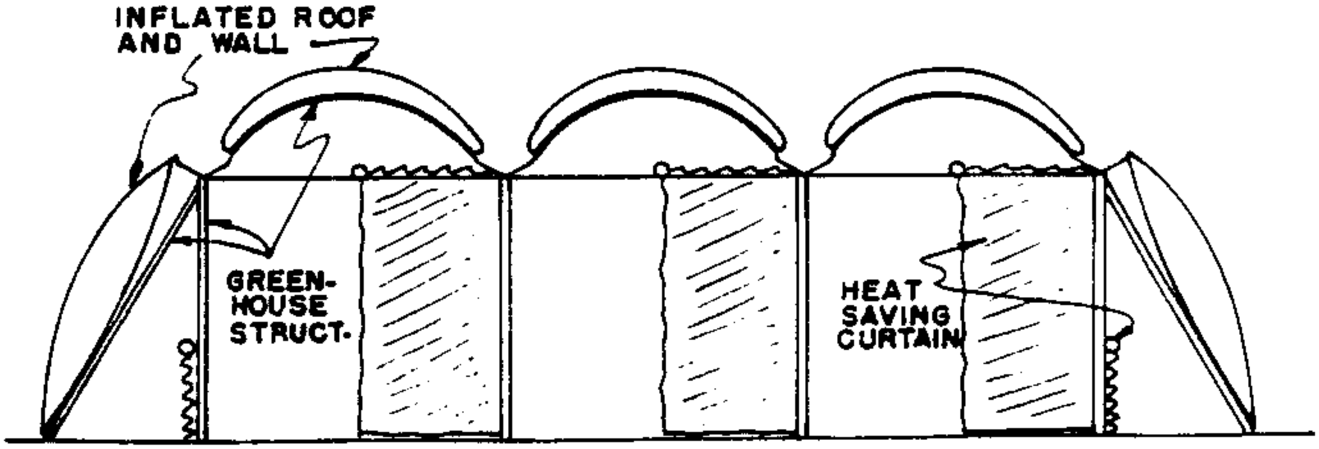
FIG.-2 EFFICIENCY CURVE FOR SLOPED POLYETHYLENE FLAT—PLATE COLLECTOR



TYPICAL DRIVE SECTION



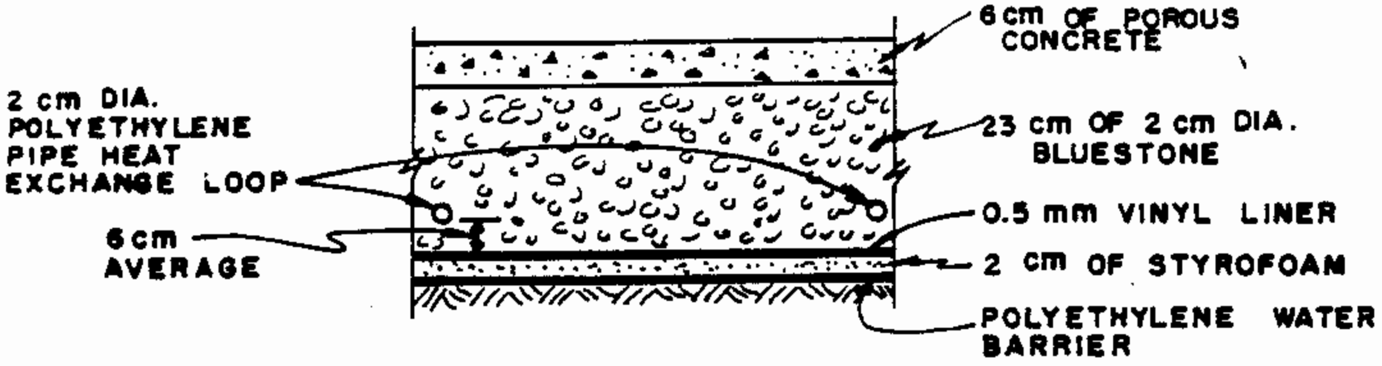
SUPPORT SECTION BETWEEN DRIVE SECTIONS



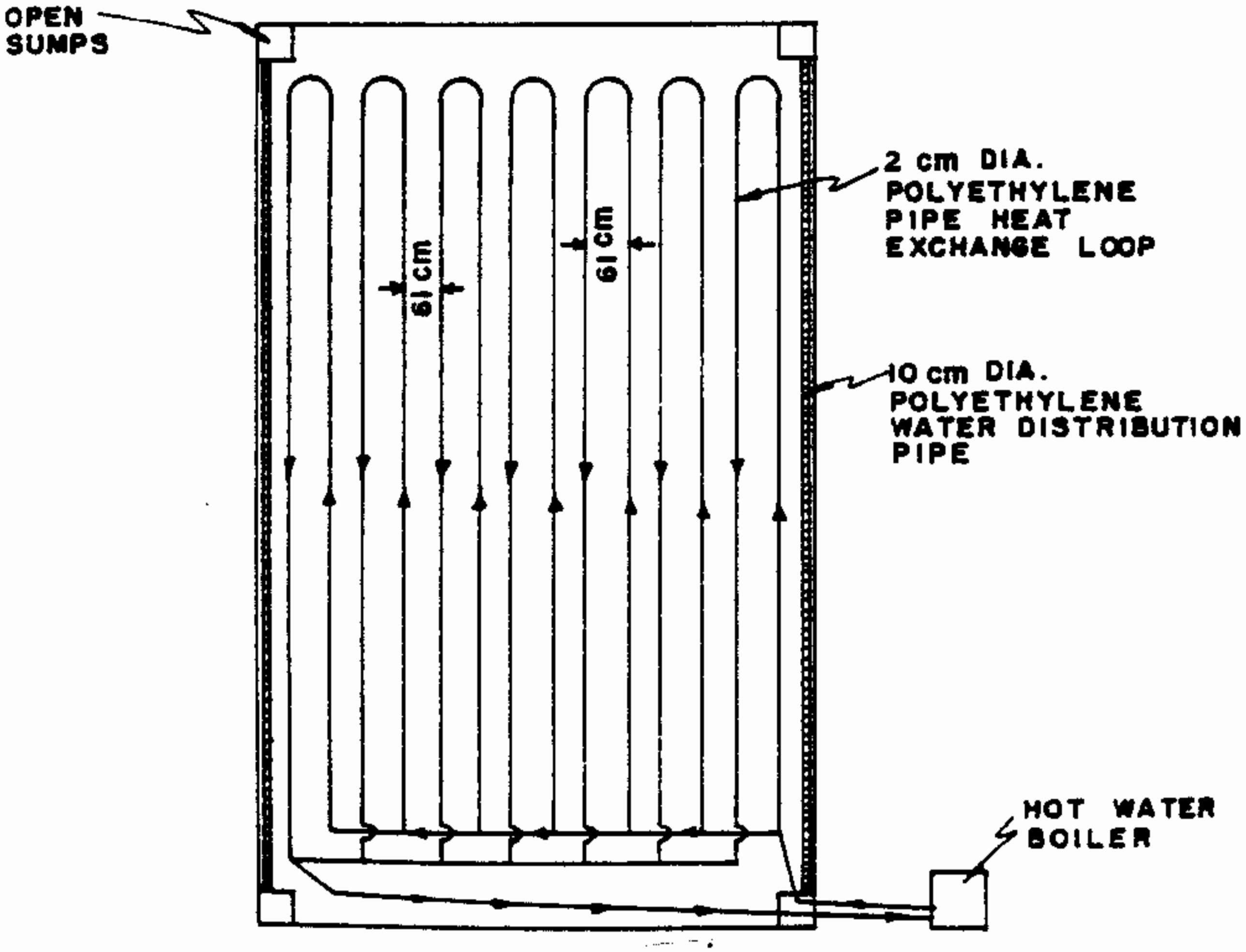
END VIEW

PARTIALLY CLOSED HEAT SAVING CURTAIN

FIGURE - 3 MOVABLE HEAT SAVING CURTAINS



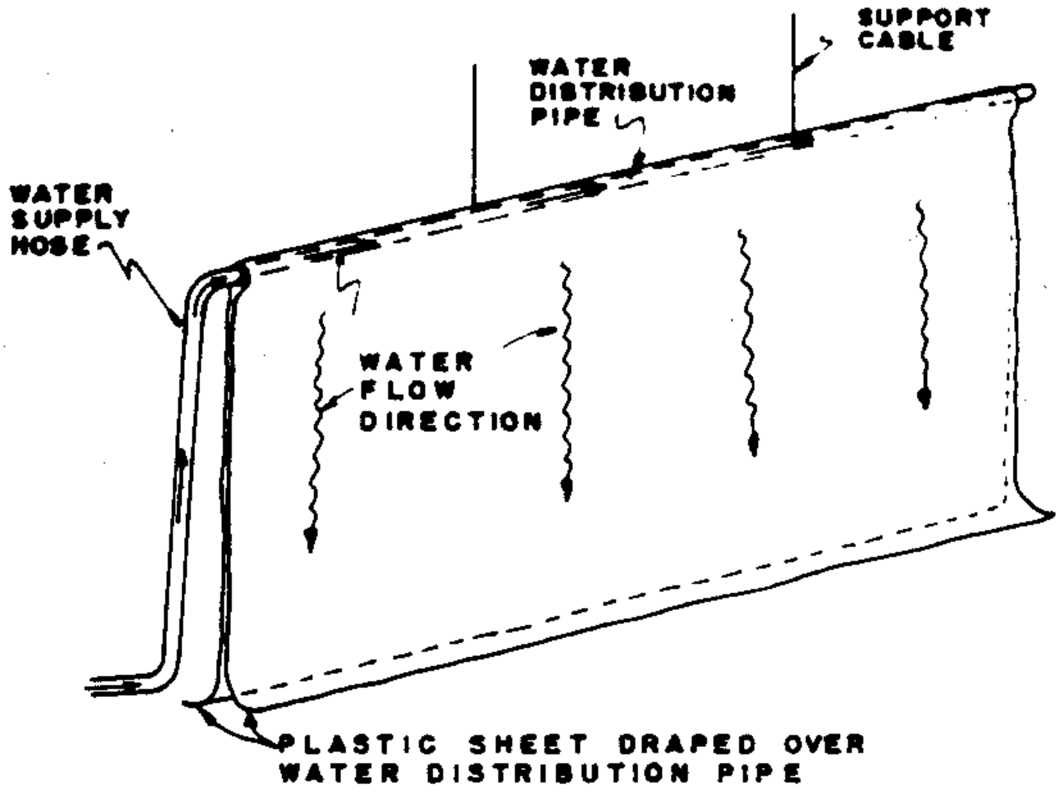
POROUS CONCRETE FLOOR CROSS SECTION



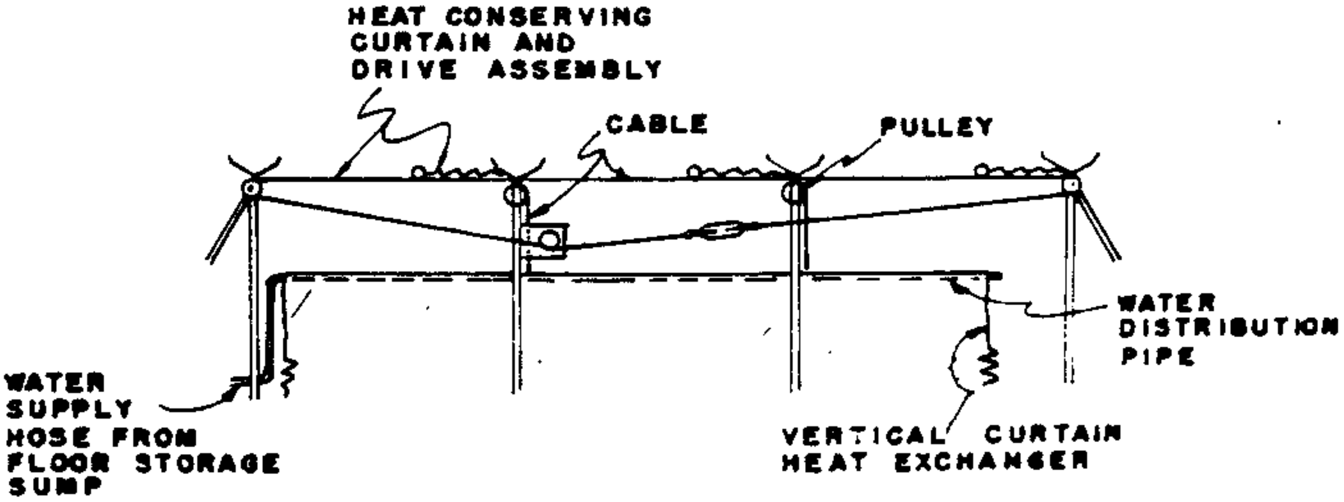
PLAN

FOSSIL FUEL BACK-UP UNDERFLOOR HEAT EXCHANGE LOOP

FIGURE - 4 DETAILS OF FLOOR HEATING SYSTEM



PLASTIC VERTICAL CURTAIN HEAT EXCHANGER



VERTICAL CURTAIN HEAT EXCHANGER INTEGRATED WITH HEAT CONSERVING CURTAIN SYSTEM

FIGURE - 5 VERTICAL CURTAIN HEAT EXCHANGER SYSTEM

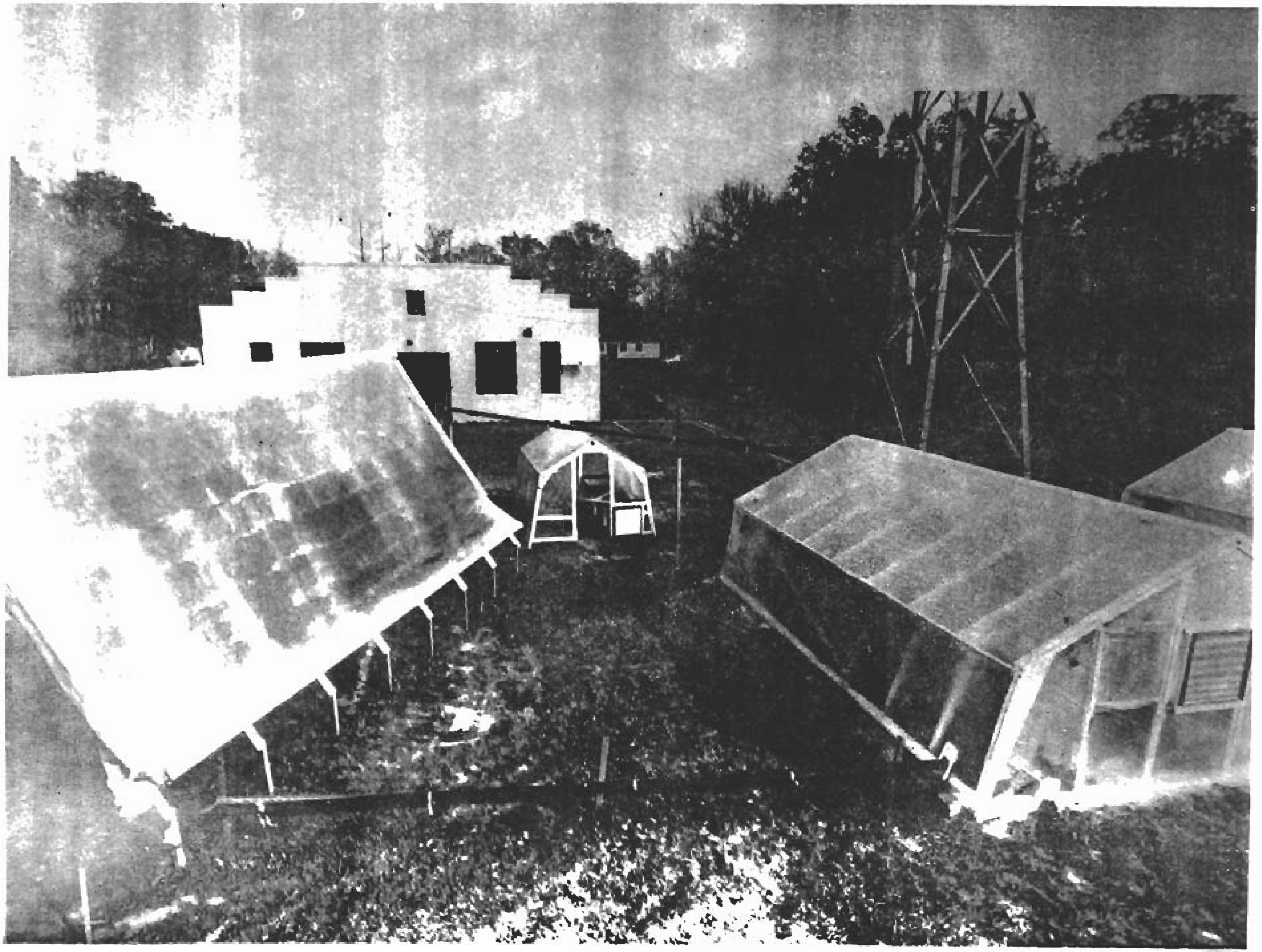


FIGURE – 6 TEST GREENHOUSE AND SOLAR COLLECTOR

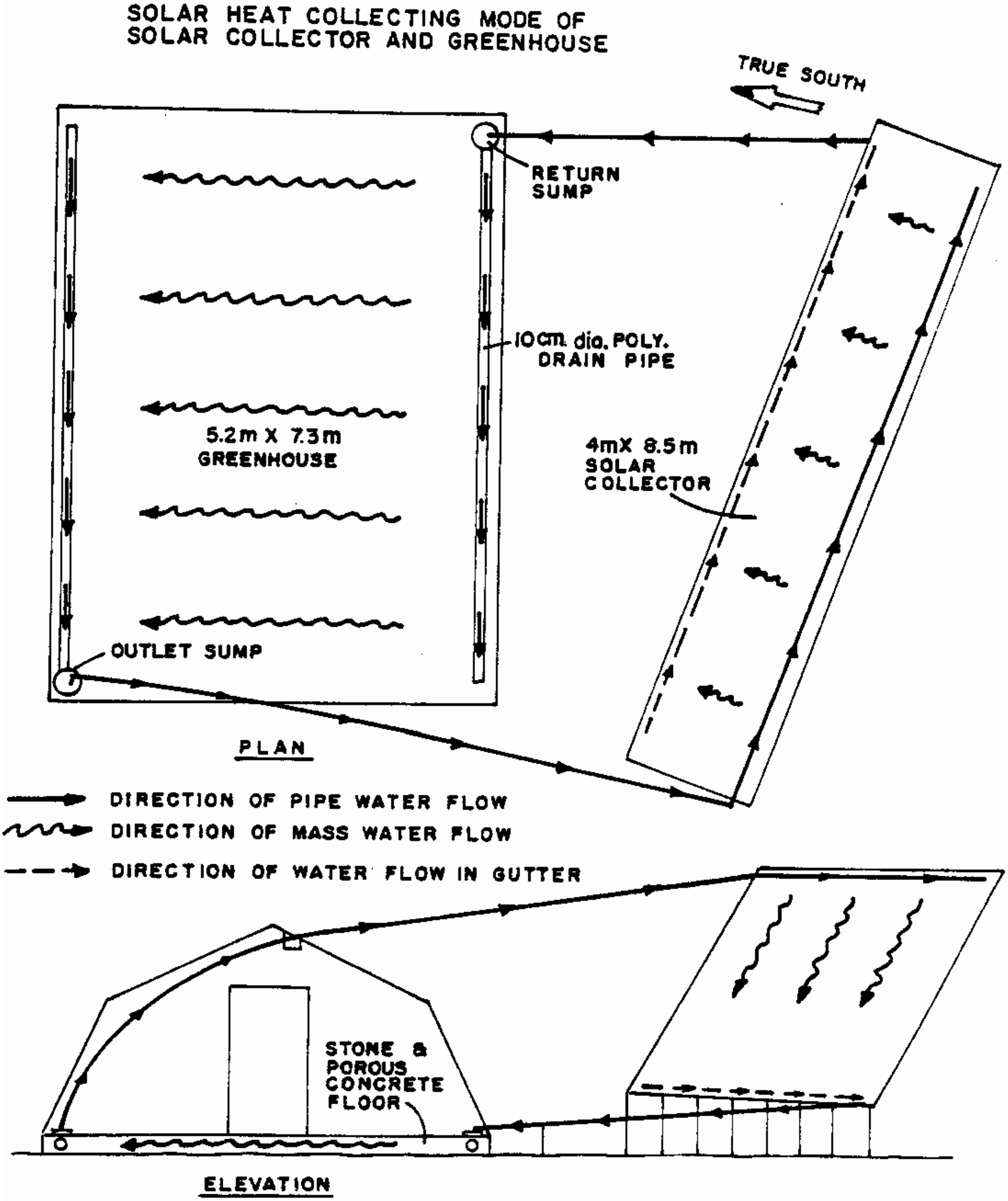


FIGURE - 7 WATER FLOW IN SOLAR SYSTEM

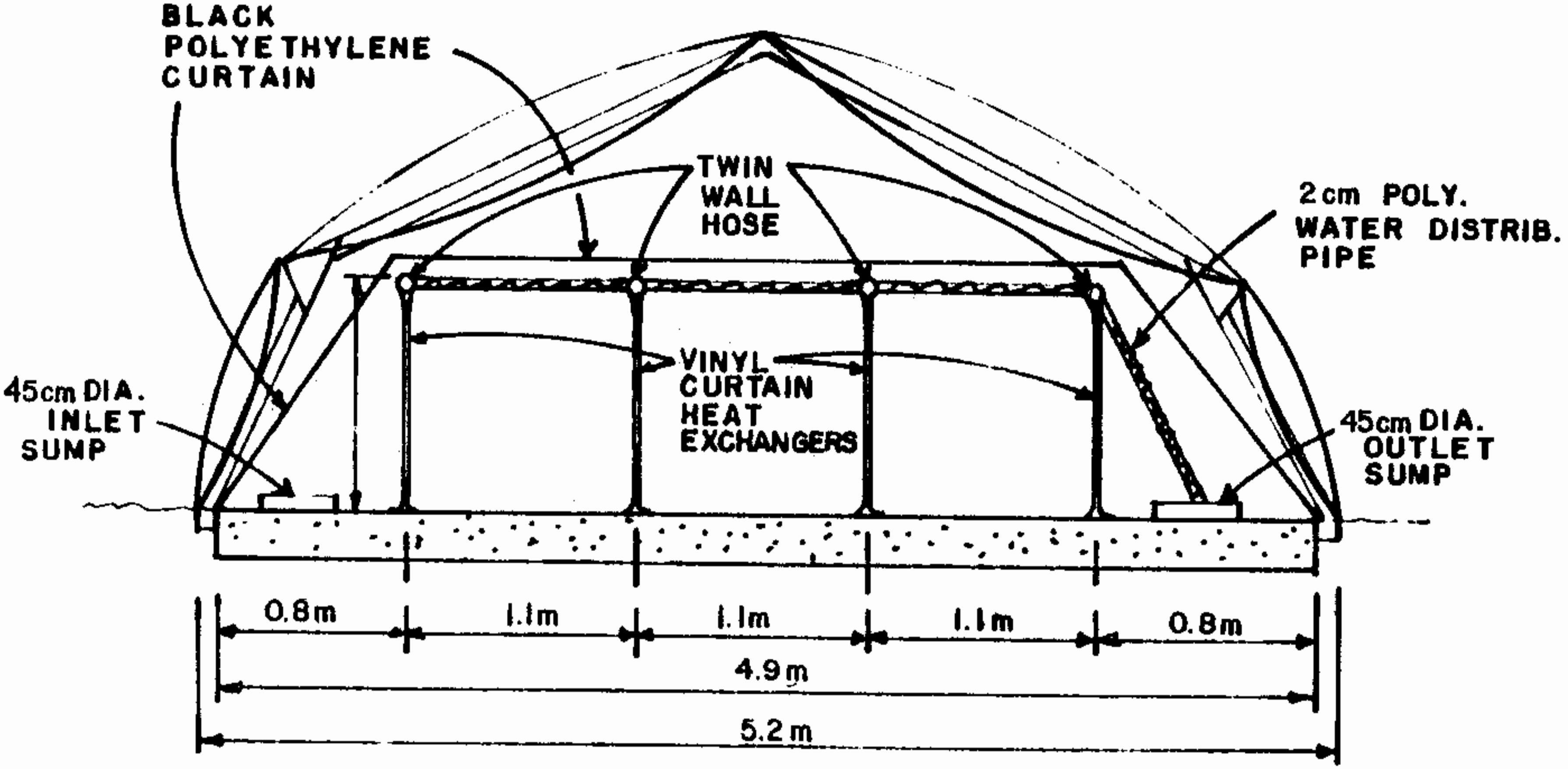


FIG. 8 DOUBLE - LAYER AIR - INFLATED 5.2m x 7.3m POLYETHYLENE GREENHOUSE WITH POROUS CONCRETE FLOOR, BLACK POLYETHYLENE CURTAIN AND VINYL CURTAIN HEAT EXCHANGERS

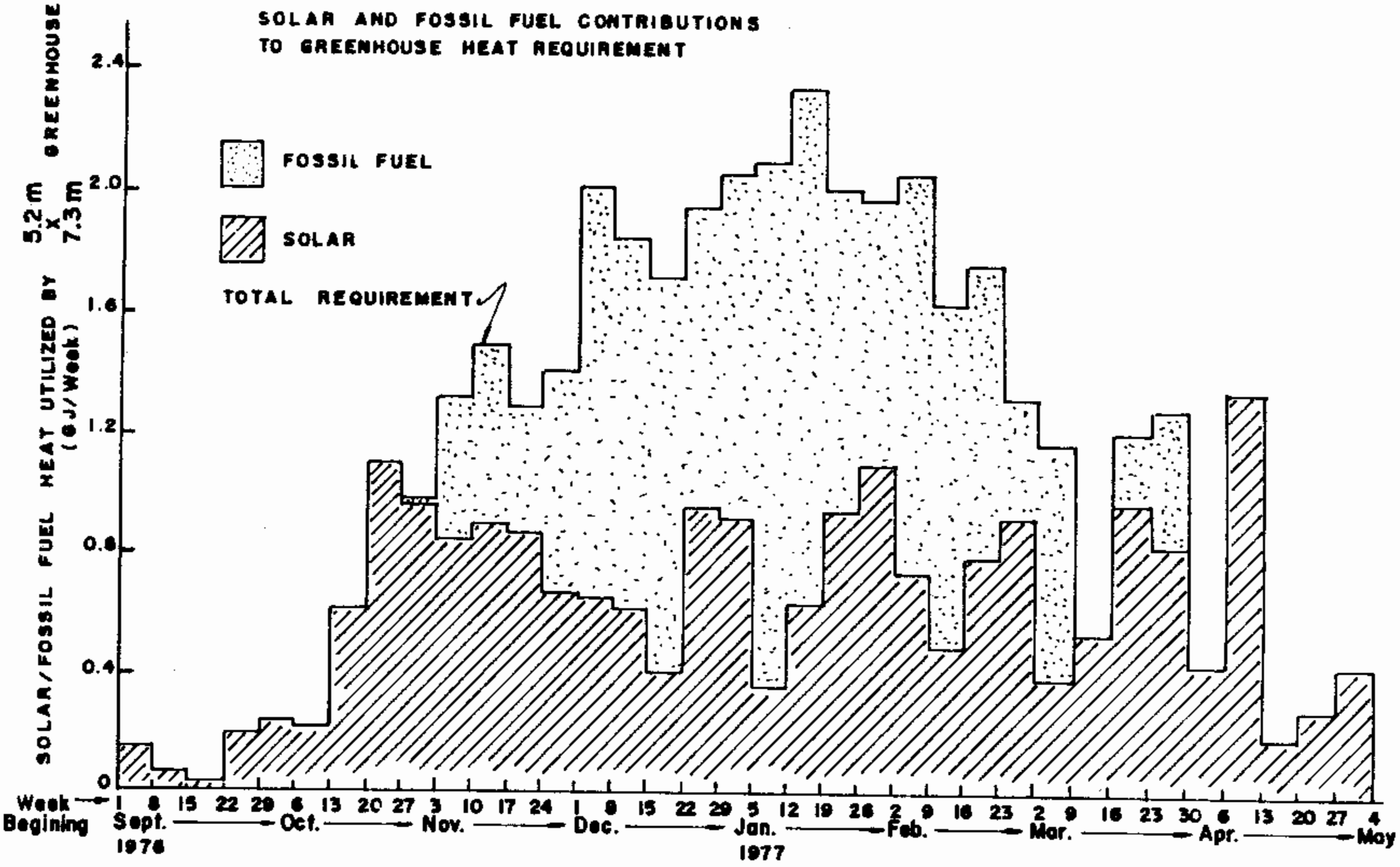


FIGURE - 9 ENERGY USE IN TEST GREENHOUSE

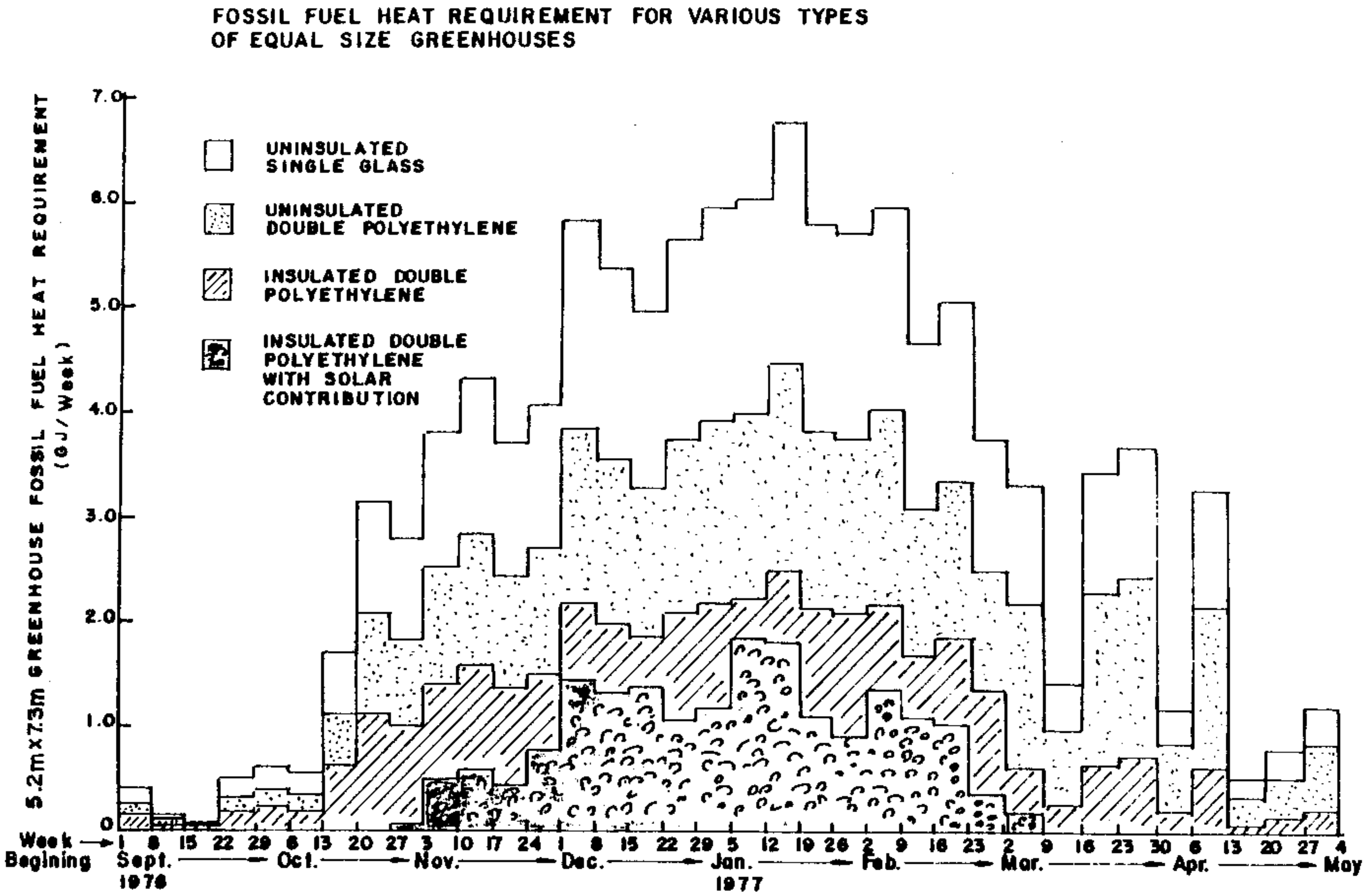


FIGURE - 10 PREDICTED ENERGY USE IN PROPOSED GREENHOUSES