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NEW CONCEPTS IN GREENHOUSE HEATING

by

David R. Mears
Associate Professor
William J. Roberts
Chairman
Joel C. Simpkins
Research Intern

Department of Biological & Agricultural Engineering
Cook College
Rutgers-The State University
New Brunswick, New Jersey

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SUMMARY: Heat loss due to longwave infrared radiation from double filmed, air-inflated polyethylene greenhouses can be significantly reduced. Methods of transferring low quality heat from warm water to air are proposed. Their feasibility is enhanced when radiation losses are reduced. Industrial waste heat and solar collectors are considered as warm water sources.

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Introduction:

It has long been recognized that greenhouse operations are energy intensive requiring an order of magnitude more heat per unit area than most other buildings. In 1971 it was reported that fuel accounted for 40% of the operating cost and the heating, electrical, and watering systems, 56% of the capital cost of a typical plastic greenhouse used for tomato production in New Jersey (6). These fuel figures were based on a spring crop, thereby avoiding 38% of the normal heating season on a degree day basis (7). The recent fuel crisis brought with it a dramatic increase in price of fuel and a new element of uncertainty regarding continuity of delivery. An entire crop can be lost as a result of even a very short period without any heat. The cost of a discontinuity in supply can be very great as indicated by Price (10).

Since fuel costs have always been a high percentage of the cost of operation there have been efforts to improve the efficiency of heating greenhouses. Significant heat savings can be realized by utilizing plastic film greenhouses with two layers of film having the space between them inflated. This inflated air space provides some insulation and tight construction reduces air exchange with the outside. Polyethylene films are more transparent to infrared radiation than glass, but plastic houses require only two thirds the heat needed for single glazed glass or fiberglas construction (13). Additional energy savings can be achieved by maintaining a tight structure, following crop development and using only the minimum heat required, growing some crops for longer periods at lower temperatures or closing down a portion of the range (7).

Maintaining condensation on the inner film layer at night reduces radiation losses because water vapor is relatively opaque to infrared radiation (13). Table 1 indicates the relative fuel savings that can be achieved for various changes in greenhouse temperature for various average outside temperatures (7).

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Table I

Percentages of Fuel Savings Potential for Various Greenhouse Temperature Reductions at Several Average Outside Temperatures

	Inside Greenhouse Temperature Reduction from A to B					
Average Outside Temperature	65°F to 60°F %	65°F to 55°F %	60°F to 55°F %	60°F to 50°F %	55°F to 50°F %	55°F to 45°F %
20°F	11	22	12	24	14	28
24°F	12	24	14	28	16	32
28°F	13	26	16	32	19	38
32°F	15	30	18	36	22	44
36°F	17	34	21	42	26	52
40°F	20	40	25	50	33	66
44°F	24	48				
48°F	29	58				

Some Proposed New Concepts:

The recent energy crisis has precipitated a flood of writing and talk about "new" ideas relating to energy. Most of the concepts can be found in the literature. In this discussion the authors are attempting to suggest how these concepts might be combined with their new ideas to provide practical new designs and greenhouse management systems. The research work is at a very early stage and this discussion is a preliminary presentation. It is hoped that this work will be of interest and helpful to those working in this area.

Many discussions regarding sources of heat for buildings, especially greenhouses, have centered on the utilization of waste heat discharged from industry or power generation stations (11, 15). The cooling water from such a source represents vast amounts of energy at low temperatures. Usually extraction of the heat for utilization is not practical using current technology.

A typical study was recently conducted in Texas relating to the heating of a greenhouse with industrial cooling water (8). There was available 140,000 gpm of water at an average temperature of 86.5°F (105°F to 70°F). A plan to heat a 40 ft by 100 ft plastic-covered greenhouse was developed. The greenhouse required 526,266 Btu per hour based on an overall heat transfer coefficient of 1.2 Btu per hour per square foot per degree Fahrenheit. The coefficient was picked to provide a 50 percent margin of safety. Water at 85°F was to be the heat source. 2,640 ft of 1 inch plastic pipe was buried in the soil for soil warming. To heat the air a heat exchanger made up of 2,300 ft of 0.5 inch copper tubing was required. The soil surface would be maintained at 70°F and 43,760 Btu per hour would be provided by the soil. The additional 482,506 Btu per hour must be supplied by the water to air heat exchanger. The heat exchanger requires a fan system to move air at 150 fpm.

The new concepts in greenhouse heating being considered by the authors are related to certain assumptions and constraints. A heating system is needed to utilize low quality heat which will exploit sources of thermal energy which have low energy costs in monetary and environmental terms. Secondly, it is assumed that some important crops cannot tolerate high humidity produced in a direct air/water contact type of heat exchanger. Conventional dry heat exchangers have high capital cost per unit heat transfer capacity when temperature differences are small. Greenhouses require a uniform distribution of heat. Heat exchangers must not interfere with the transmittance of light especially in the winter when available light is the limiting factor. Heat exchangers should not interfere with the work that must be done in the structure.

The major structural item in a plastic-covered greenhouse is the polyethylene film which is a thin, strong, transparent material available at low cost. This material can make a low cost per unit area heat exchanger capable of maintaining separation between air and water. Consider first the possibility of floating a greenhouse with a continuous plastic floor on a pond of warm water being discharged from an industrial operation as depicted in Fig. 1. The temperature in the house will depend on the outside and pond temperatures and the relative heat transfer coefficients at the floor, roof, and side wall. If the plants are grown on the floor as shown in the figure, soil temperatures will be higher than inside air temperatures. Instead of floating a single house, a series of houses could be constructed over a large warm water pond with a plastic floor as shown in Fig. 2. There are many possible and interesting techniques of engineering such structures.

Another large area available for heat exchange is the roof and sidewall as shown in Fig. 3. The warm water is to be delivered between the two layers of plastic through a supply manifold located at the ridge. The water then flows in a sheet down the inner film layer and sidewalls to be collected in a return gutter. This technique heats the space between the layers which has been used as thermal insulation, and increases the total rate of heat loss for the system. This would not be an important factor if the warm water source is otherwise waste heat, and would be beneficial if a secondary objective is the cooling of the industrial water. A possible problem might be the disturbing nature of moving light patterns and disorientation of people working in a house with moving ripples in the flowing sheet of water. It is hoped that steady state sheet flow within the film envelope will not create such a problem. This heating concept could be extended to large multispan structures as shown in Fig. 4. A fringe benefit of such a system might be the incorporation of partial shading required for some crops during maximum light periods in the summer. Dye could be added to a recirculating water supply to adjust the opacity of the roof to the desired levels. Some problems of staining have been observed with this technique.

The systems discussed in this paper all show the growing media contained in long troughs 1 ft deep by 2 ft wide resting on the floor. A subirrigation system for these has been developed utilizing corrugated plastic drain line at the bottom of the bed running the entire length (9). A 20% yield increase of tomatoes was obtained over beds 8 inches deep watered from the top. In an effort to warm the beds, warm water was used for irrigation, but it was found that bed temperatures dropped rapidly after a water application, approaching the soil temperature within 30 minutes. Another attempt to warm the soil in one tomato house entailed the construction of ducts using the beds as sides and the top as a walkway level with the tops of the beds. The warm air from the heating units was delivered to the passage between the beds under the walk by a manifold at the end of the greenhouse. The warm air left the ducts through small slots next to the beds. This system was effective in maintaining warm beds resulting in increased earliness but no change in total yield.

In an effort to develop a simpler way to deliver heat to the soil, an experiment was conducted on a small scale this past winter. Three beds were constructed with buried plastic drain extending through both ends of the bed. At one end of each bed a box was installed with a float valve to maintain a constant water level as shown in the cross sectional view of a bed in Fig. 5. One bed was a control, one had room temperature air blown continuously through the space in the pipe over the water, and in the third, the water was continuously circulated through a tank with an electric heater. Although the data have not been completely analyzed several general conclusions can be reached. The continuous circulation of room temperature air through the irrigation pipe did not significantly increase the bed temperature. The water circulation system appears capable of maintaining the average bed temperature at any desired level. For example, keeping the circulating water at 85°F, the average temperature near the top was about 70°F, which is the condition obtained in the soil warming study in Texas discussed previously (8).

Although the watering system has been found satisfactory in normal use (9), it has become evident that when warm water is continuously recirculated the problem of roots entering the pipe is accelerated. This condition is most likely to occur under the conditions of this warming study in which the nutrient-rich warm water was aerated on each pass through the system producing ideal conditions for root growth. Therefore, a test is planned in which the soil-warming and subsurface irrigation operations will be separated as shown in Fig. 6. Irrigation water can be added through the pipe as needed. Warm water can be continuously circulated through the two plastic film tubes laid in the bottom of the trough on either side of the pipe. The circulating water should be under sufficient back pressure to support the weight of the mix. In this way a constant source of dry heat will be available to warm the beds without influencing soil moisture or inducing root growth in the subirrigation pipe.

In order to do analytical work relating to the transfer of heat through the artificial mix, it is necessary to know the thermal properties of the material. Therefore, determinations of the thermal properties of the mix (50% peat moss, 50% vermiculite) were made over a wide range of moisture contents. The techniques used to measure specific heat and thermal diffusivity were developed during a project on composting animal wastes and are described by Ali (1). The measured values of the specific heat and the values for thermal conductivity calculated from the thermal diffusivity determinations are presented in Fig. 7. The curves have been hand fit. The recommended moisture content for the mix is in the range of 75% wet basis.

Instead of floating an entire house over a pond of warm water, it might be better to use the system already discussed to warm the troughs in conjunction with a warm floor between the planting rows. Some work has been done by the authors utilizing long tubes of polyethylene film lying flat on the ground as heat exchangers. Enough water can be put into the tube to fill it to the desired depth and flow through the system can be controlled. Physical damage to the surface could be a problem.

In order to evaluate the possibilities of such a concept, a series of computations has been performed to determine the required water temperatures under various circumstances and the results are presented in Table 2. In order to make these calculations, it was assumed that the crop would be tomatoes for which the maximum recommended soil temperature is 70°F (5) and the minimum air temperature under favorable growing conditions is 60°F (5, 14). The first five cases are for the "Rutgers 700", a 29 ft by 96 ft plastic-covered house with a slant-leg wood frame. Cases 6 through 8 are for a house sold by Van Wingerden Greenhouses, Inc. and available in widths which are multiples of 12 ft. This multispan house covering almost 3 acres has an exposed roof and wall area to floor area ratio of 1.2 in contrast to the individual house which has a 1.6 exposed area to floor area ratio.

Case 1 shows what would happen if the house were covered with fiberglas in which case the accepted overall heat transfer coefficient would be 1.2 Btu per hour per square foot per degree Fahrenheit. Assuming an outside design temperature of -10°F a total of 375,000 Btu per hour would be required to maintain the inside at 60°F. If 85°F water would keep the beds at an average temperature of 70°F as indicated earlier and if the heat transfer coefficients from the sides and tops of the troughs were 1.46 and 1.63 respectively (4), the troughs would add about 33,200 Btu per hour. The additional heat could be supplied from the remaining floor surface if it were held at an average temperature of 183°F assuming a heat transfer coefficient of 1.63. Changing the greenhouse cover to a double layer of polyethylene film as recommended, will reduce the overall heat transfer coefficient of the building to 0.8 (13). In case 2 with all other factors the same the floor temperature required is 138°F.

Research is underway to determine the mechanisms of heat transfer from plastic-covered greenhouses. As a part of this investigation, test sections of a fully instrumented greenhouse have been covered with various materials to determine the effects of radiation heat loss. Preliminary indications are that a reflective covering can reduce the total heat loss on a clear night by as much as 40 percent when the inside-outside temperature difference is about 40°F. Techniques have been developed for automatic black cloth shading for light control (12). A system utilizing a covering material selected for its reflectance of infrared radiation has a potential of reducing the design heat transfer coefficient for a cold clear night from 0.8 to 0.5. Development of a polyethylene film with additives to block the transmission of infrared radiation could have a similar effect. The results of such an installation are given in case 3. The required floor temperature is reduced to 104°F.

Table 2

DESIGN CONDITIONS FOR FLOOR HEATING WITH 70°F SOIL TEMPERATURE

Case	House Size ftxft	Type of Cover on House	Design U Value $\frac{\text{Btu}}{\text{hr ft}^2\,{}^\circ\text{F}}$	Outside Air °F	Inside Air °F	Total Heat Requirement Btu/hr	Heat from Plant Troughs Btu/hr	Required Floor Temperature °F
1	29x96	Fiberglas	1.2	-10	60	379,000	33,200	183
2	29x96	2 Layers of Polyethylene	0.8	-10	60	253,000	33,200	138
3	29x96	2 Layers of Polyethylene & inside radiation cover	0.5	-10	60	158,000	33,200	104
4	29x96	2 Layers of Polyethylene & inside radiation cover	0.5	-10	55	147,000	49,800	89
5	29x96	2 Layers of Polyethylene & inside radiation cover	0.5	-5	55	135,000	49,800	85
6	210x576	2 Layers of Polyethylene	0.8	-10	60	8,170,000	1,480,000	116
7	210x576	2 Layers of Polyethylene & inside radiation cover	0.5	-10	60	5,100,000	1,480,000	90
8	210x576	2 Layers of Polyethylene & inside radiation cover	0.5	-10	55	4,760,000	2,220,000	76

When heating a greenhouse with low temperature source radiation it has been found that plant leaf temperatures and a radiation sensor maintain themselves on the order of 5 to 10°F warmer than the ambient air temperature during the coldest hours of the night (2). In our investigation we have found typical black body temperatures in the test greenhouse on the order of 5°F colder than ambient temperatures on clear nights when there is a 40°F inside-outside temperature differential. When reflective material is used for radiation shielding the black body temperature approaches the ambient. If it has been found that 60°F air temperatures are adequate for tomatoes at night, it may well be that actual plant temperatures may be closer to 55°F on clear nights when radiation losses are the greatest. This suggests the possibility that elimination of this radiation heat loss would permit a lowering of the inside air temperature to 55°F without harm to the plant. This condition is illustrated in case 4 which shows an increase in the heat coming from the troughs and a reduction in the required floor temperature to 89°F. As shown in case 5 a -5°F outside temperature design would allow for 85°F water to be used for both trough and floor heating.

In the larger house, cases 6, 7, and 8, similar conditions are assumed as those already discussed. The required floor temperatures are significantly reduced because of the better ratio of exposed structure to useful floor in this building. By interpolating cases 7 and 8, it can be seen that 85°F water for both troughs and floor would hold the inside air temperature between 55°F and 60°F even when it was -10°F outside.

It has often been noted that during some of the greenhouse heating season there is daytime removal of excess heat by ventilation. It has also been suggested that solar heat be stored for night use in greenhouse heating. Presumably some heat can be removed from the exhaust warm air during ventilation by drawing it through a direct air/water heat exchanger. Even though the quality of this heat would be low, it would be possible to heat limited quantities of water to temperatures suitable for soil and floor warming. This water would need to be stored in a tank for later use. Dry type heat exchangers such as rocks or tubes containing eutectic salts with a fusion temperature on the order of 85°F could be used if the costs were acceptable.

There has been extensive discussion on the use of collected and stored solar heat being utilized for greenhouse heating. One well publicized concept for home heating utilizes black painted corrugated aluminum roofing overlaid with glass plates as the solar energy collector (3). In order to heat a well insulated residence the collector area dominates a section of roof pitched to the south, hence the collector area is similar to the building area. However, a greenhouse has a heat loss rate about 10 times as great as an insulated residence. Therefore, a solar collector for total greenhouse heating would have to be about 10 times the area of the greenhouse being heated.

Solar collectors are more efficient at low working temperatures. They may have a legitimate place when used with the previously discussed low-temperature heating system. If simple collectors could be made to meet these requirements with unit costs about one tenth those of residential collectors which now are on the verge of competitiveness, the outlook for practical application would be greatly improved.

Some preliminary tests have been conducted to determine the feasibility of initiating further research on the collection, storage and utilization of solar energy in greenhouse heating. The data presented here are the results of measurements which should be repeated under a more accurate experimental regimen before being accepted, but they should serve as a point of departure for thinking on this subject. The solar heat collectors investigated so far have all been based on the idea of using long plastic tubes on horizontal surfaces and partially filled with water in the same manner as the floor heat exchangers previously discussed.

In one test short sections were put out partially filled with water. These tests served to compare several different ways of utilizing polyethylene tubing by comparing the maximum temperatures obtained by each. In each case clear, 4 mil polyethylene tubing 1.5 ft wide when flat was used to contain the water. The least satisfactory system was the plain tubing placed on top of a reflective, insulated surface. In one test the water in this section reached 126°F when the incident solar radiation was 256 Btu per hour per square foot. Under the same conditions an equally efficient system was the plain tubing laid out on blacktop which also reached 126°F. When a sheet of black plastic was placed under the tubing the temperature was increased to 132°F. Slipping a sheet of black plastic inside the plain tube increased the temperature to 135°F. When such a section was placed on top of insulation and the top layer of plastic raised up about an inch over the water, there was a further increase in temperature to 142°F.

After obtaining these results it was decided that the plain tube with the black plastic insert would be the best system to test as a solar heat collector. Although several different types of test have been conducted a discussion of one in particular will illustrate the potential of this idea. Identical collectors were laid out on flat surfaces, one under a greenhouse roof and the other in the open sun. Each was 1.5 ft wide, 10 ft long and had water flowing through at a rate of 4.4 lbs per minute in sheet flow. The inlet water temperature for both was 72°F and when the solar intensity was 268 Btu per hour per square foot, the unit in the sun had an outlet temperature of 86.5°F for a heat collection rate of 255 Btu per hour per square foot and a collection efficiency of 95%. The unit in the greenhouse had an outlet temperature of 83.5°F for a heat collection rate of 202 Btu per hour per square foot and a collection efficiency of 76%. These results indicate the reduction in available solar energy for collection inside the greenhouse. While solar collectors could be placed in the walkways and along a north wall, this reduction and the limited areas available dictate that for a solar greenhouse to be technically feasible there must be a solar heat collection system outside the house. Increased working fluid temperatures have been obtained by increasing the ratio of collector area to water flow rate and by recirculating the heated water through a storage reservoir as would be done in a complete system. The collection efficiency will be reduced as the difference between the temperature of the working fluid and the environment around the system increases.

In order to heat the house of case 3 in Table 2 on a winters day with an average temperature of 10°F and assuming that on that day a total of 400 Btu per square foot per day would be available on a horizontal surface (4) and that the total system operates on a 75 percent efficiency, there would have to be about 9,000 square feet of collector. This area is more than three times the floor area of the greenhouse. If the system were to store enough heat for three to five sunless days as advocated in residence heating systems (3), the collector area to greenhouse floor area would be increased to from ten to sixteen times.

Suggestions for Further Research:

In our opinion, the greatest potential for improving the situation regarding energy in greenhouse heating lies in the area of developing practical means of utilizing low quality energy. The most important area of research in this regard is the development of heat exchange systems that are extremely low in cost per unit area and will effectively control temperature and humidity. The ideas discussed in this paper need to be tried out on a pilot scale. Measurements of the important parameters need to be made under a wide range of operating conditions so that theoretical analyses can be verified and coefficients required for design work determined. Effective means of constructing and installing plastic film heat exchangers need to be perfected and their reliable life determined. Utilizing these data, proposed designs can be developed and evaluated using computer simulation.

Having developed satisfactory greenhouse heat exchangers, the feasibility of utilizing various potential sources of "waste" heat can be determined. In addition to economic factors the location and reliability of the source are important. Systems simulation studies can serve to indicate the importance of various factors but ultimately pilot operations should be designed, built and evaluated. Also, more needs to be known regarding plant response to different methods of heating. For example, to what degree will soil heating compensate for reducing air temperatures and what is the relative importance of ambient air temperature and mean radiant temperature?

The concept of a solar heat collector discussed here should be investigated further. Even if there is not sufficient area to capture enough heat for the entire house, it might be practical to use such a system for warming the beds. It appears that solar heat collection becomes most practical where the required heat quality and quantity is minimized and inexpensive collectors can be developed with reasonable thermal efficiencies.

There is a great need to build and test prototype energy-conserving systems for greenhouses (as well as most other buildings and enterprises in our society). A great deal has been said and written on the subject and many panaceas are being presented to us for the energy crisis. It would appear that at this time there is a need for real opportunities to get experience with complete systems and to discover what the bugs are. It is the authors' hope that the ideas presented here will provide some stimulation for those who have an opportunity to work in this field.

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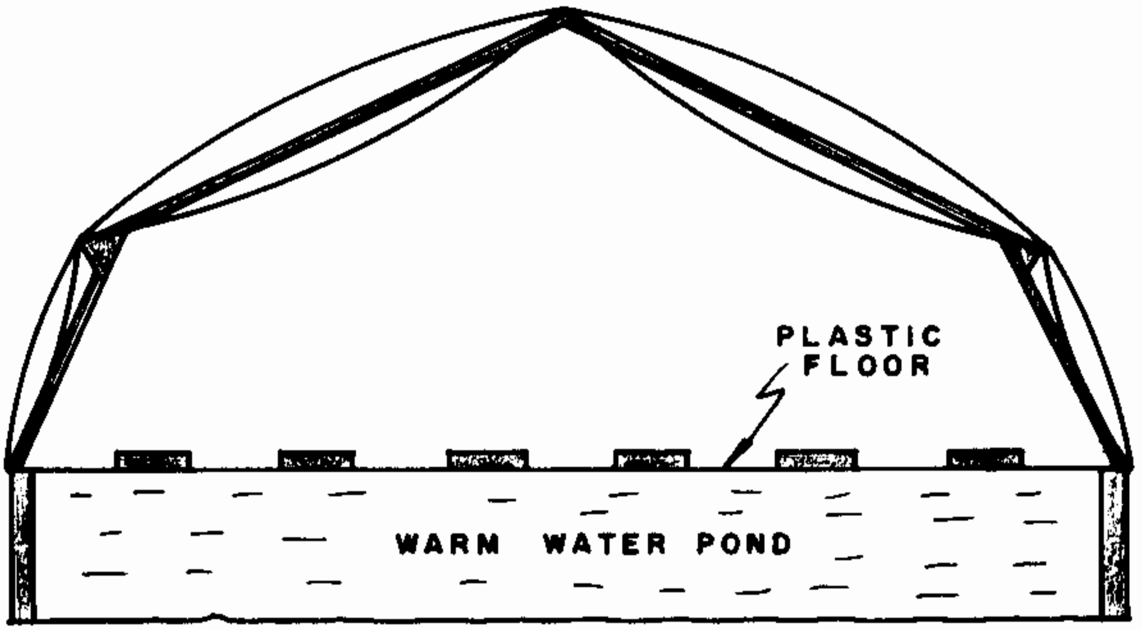

FIG-1 GREENHOUSE HEATED BY FLOATING BEDS ON WARM POND

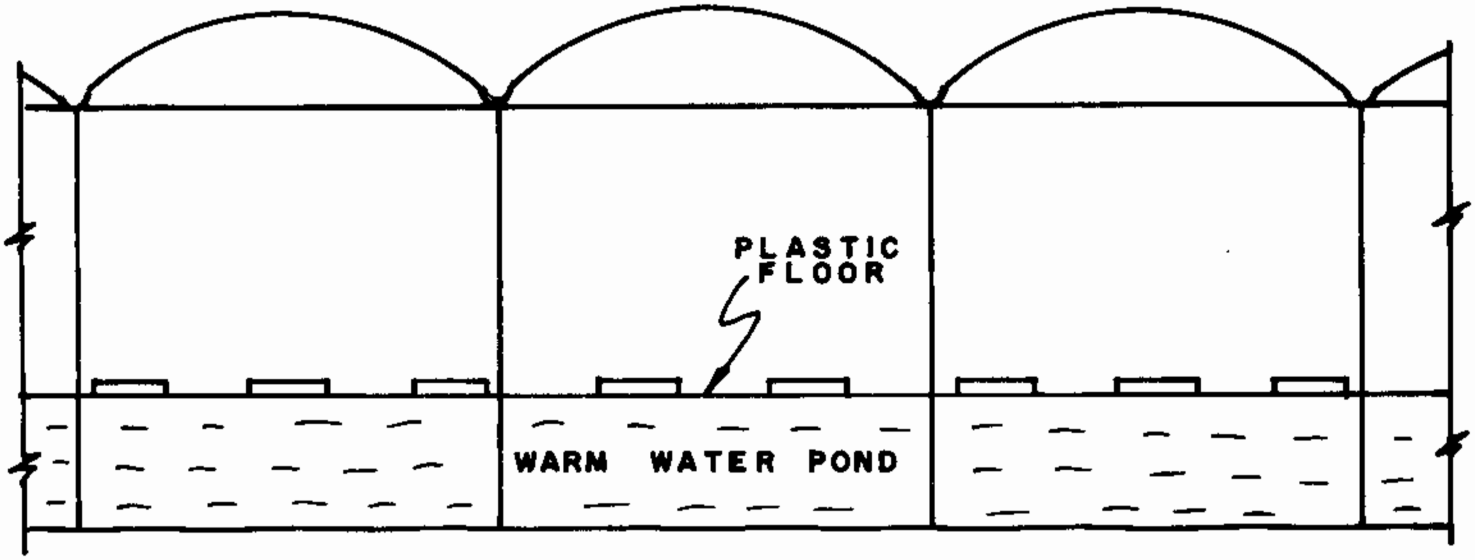

FIG-2 LARGE MULTISPAN GREENHOUSE HEATED BY WARM FLOOR BUILT OVER WARM POND

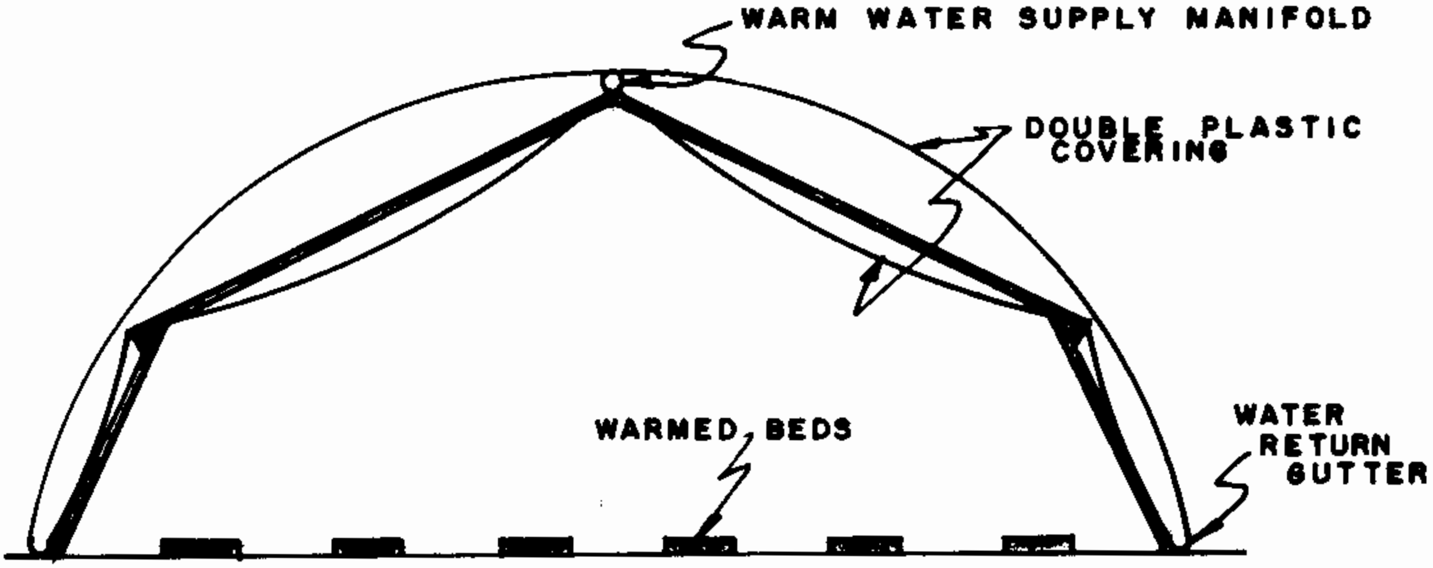

FIG - 3 GREENHOUSE HEATED BY SHEET OF WARM WATER FLOWING OVER INNER LAYER OF COVER

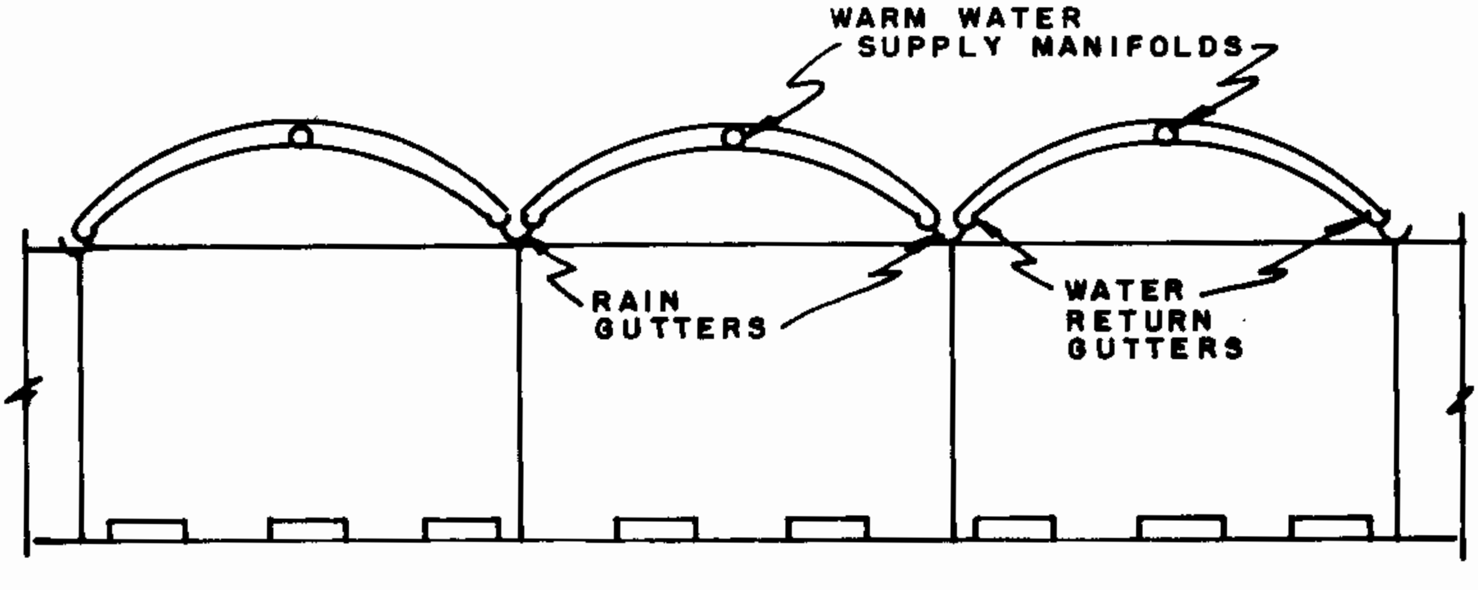

FIG - 4 LARGE MULTISPAN GREENHOUSE HEATED BY SHEET OF WARM WATER FLOWING BETWEEN LAYERS OF COVER

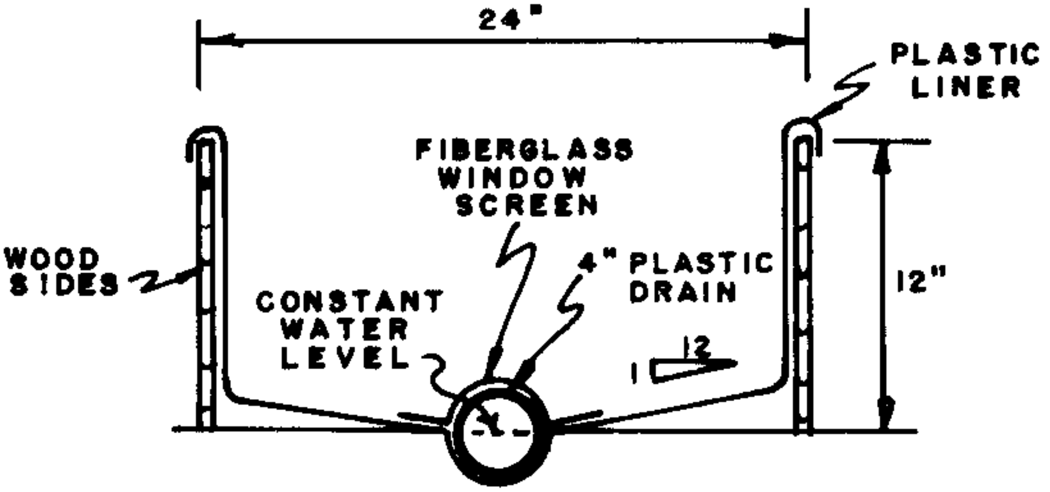

FIG - 5 CROSS SECTION OF BED WITH SUBIRRIGATION USED IN SOIL WARMING STUDY

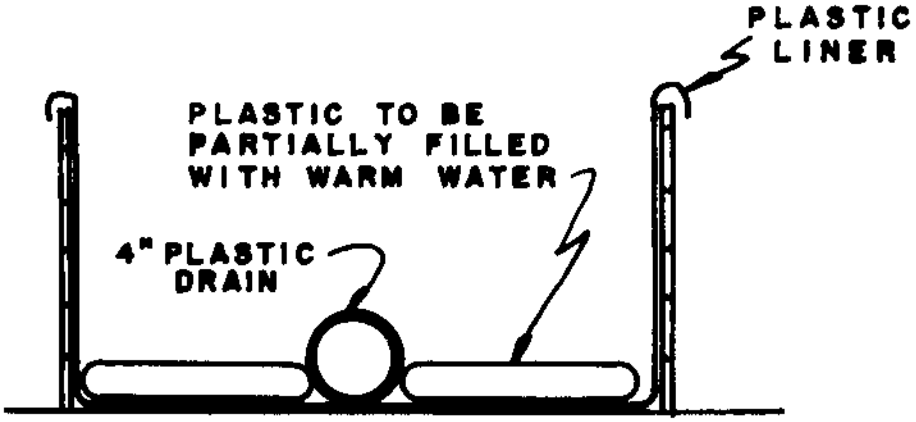

FIG - 6 MODIFICATION OF SUBIRRIGATION SYSTEM FOR DRY HEAT EXCHANGE TO THE SOIL

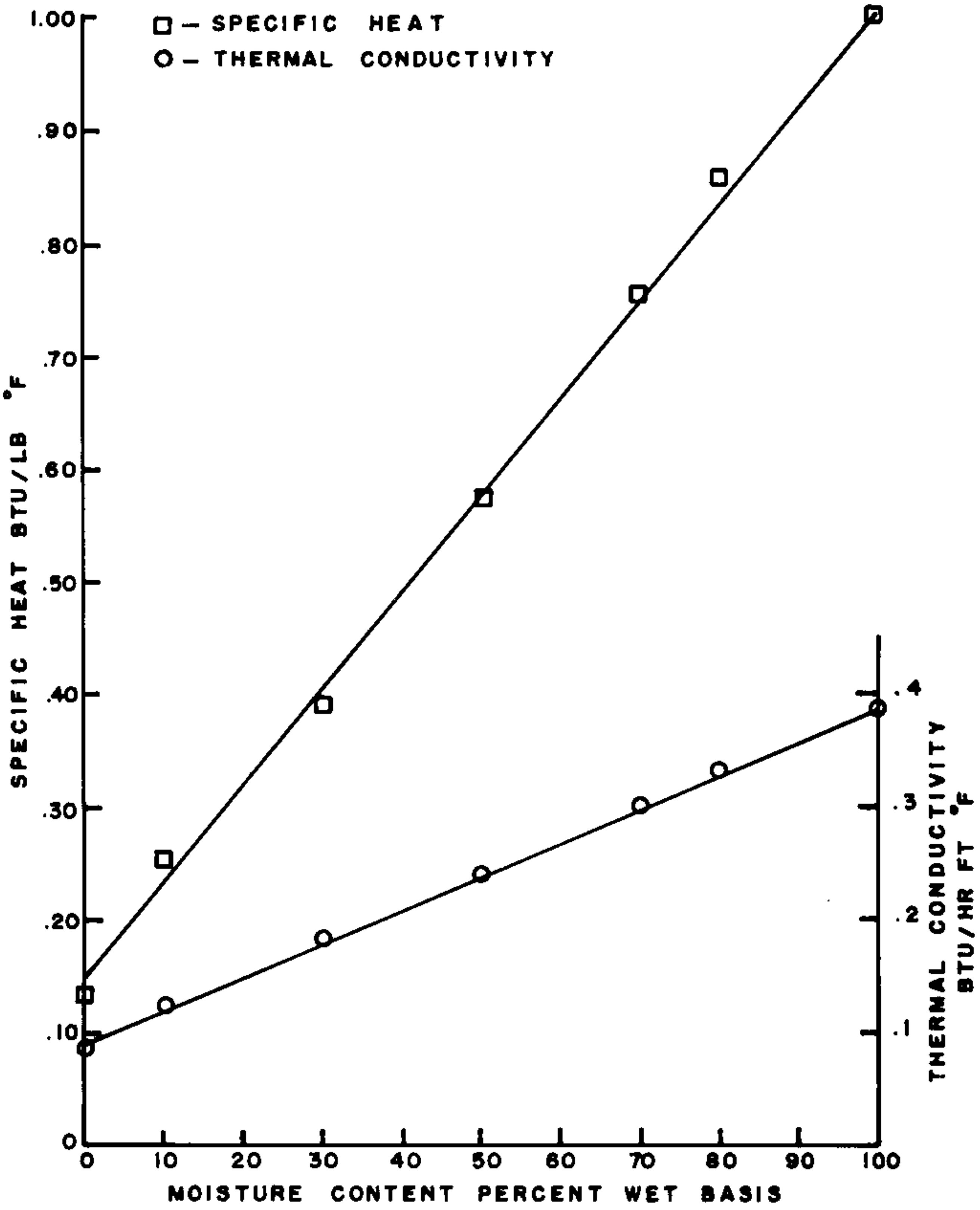

FIG – 7 SPECIFIC HEAT AND THERMAL CONDUCTIVITY OF PEAT MOSS VERMICULITE MIX