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FEASIBILITY OF WASTE HEAT UTILIZATION IN GREENHOUSES

by

T. Manning, Research Associate
D. Mears, Professor
R. McAvoy, Research Assistant
Biological and Agricultural Engineering Department
RUTGERS UNIVERSITY - COOK COLLEGE
New Brunswick, New Jersey 08903

and

B. Godfriaux, Principal Staff Senior Biologist
Public Service Electric and Gas Company
Newark, New Jersey 07101

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SUMMARY:

An experimental greenhouse was built at the Public Service Electric & Gas Company's generating station in Mercer County, NJ, in order to evaluate the feasibility of using warm water discharges from electrical power plants as a heat source for greenhouses. This prototype incorporates several concepts developed at Rutgers University for using low temperature water in conjunction with solar heating systems.

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Thomas O. Manning[1] David R. Mears[2]
Richard McAvoy[3] Bruce Godfriaux[4]

INTRODUCTION

An increasingly attractive option for greenhouse growers wishing to reduce energy consumption is the use of warm water discharges from electrical generating stations as a source of heat. Research into the feasibility of this concept has been conducted through various projects in both Europe and the United States. The heat distribution systems investigated can be roughly divided into two types: direct contact heat exchange, and dry exchangers, such as finned pipe, usually coupled with forced convection. The Tennessee Valley Authority has constructed a pilot greenhouse that is heated with air circulated through a pad wetted with the condenser discharge water from the Browns Ferry Nuclear plant(Pile et al., 1978). Several commercial scale greenhouses have been constructed at a coal-fired generating station of the Northern States Power Company in Becker, Minnesota. These greenhouses contain unit heaters housed in each bay that force air over banks of finned pipe containing the warm water from the power plant. The greenhouse soil is warmed by buried polyethylene pipes which also carry the condenser discharge water(Ashley and Hietala, 1977, Widmer, 1979).

In recent years, research on solar heating and energy conservation in greenhouses at Rutgers University has been oriented toward the use of low temperature water as a heat source. Several greenhouses have operated with heating water temperatures ranging from 24-27°C (Roberts et al., 1976, Mears et al., 1977), using several new concepts in heat exchange and energy conservation and low cost solar collectors for providing part of the heating requirement. Among the principal features of the Rutgers solar heated greenhouse are: a flooded floor storage/heat exchange system, insulating curtains, and low temperature heat exchangers (vertical curtain heat exchangers). The floor is made up of 0.5mm biocide treated polyvinyl chloride film filled with gravel

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[1] Research Associate; [2] Professor; [3] Research Assistant
Biological & Agricultural Engineering Department, Cook College -Rutgers University, New Brunswick, NJ 08903.
[4] Principal Staff Research Biologist, Public Service Electric and Gas
Newark, NJ 07101.

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and water and capped with a layer of porous concrete (see Figure 1). This floor serves as thermal storage and a heat exchange area from the warm water to the greenhouse. Automatically controlled curtains drawn across the ceiling inside the greenhouse that close at night and open in the daytime can reduce greenhouse heating loads by 30-50%, depending on the curtain materials and greenhouse type and geometry (Simpkins et al., 1976, Roberts et al., 1976). The warm floor is not sufficient to maintain optimum temperatures in an insulated greenhouse during cold weather, and additional heat exchange area is required if the warm water is to be the only source of heat. For this purpose, curtain heat exchangers have been constructed by draping plastic film over a water distribution pipe. These curtains are designed to roll up out of the way during the daytime when supplemental heat is not required.

DESCRIPTION OF PROTOTYPE GREENHOUSE

To test the feasibility of heating a greenhouse with water at 28.5°C an 11m x 12.2m gutter-connected double-covered polyethylene greenhouse was built at the Mercer County Generating Station near Trenton, New Jersey. The heating and energy conserving components in this greenhouse were modeled after those in Rutgers solar heated greenhouses. The first stages of construction on the greenhouse involved the installation of a 7.3m x 12.2m porous concrete floor. The greenhouse structure, a 2 bay gutter connected design, was assembled over the concrete floor, and covered with a double layer of polyethylene film (see Figure 2).

A black vinyl-aluminum mylar laminated material was used for overhead insulating curtains running parallel to the greenhouse gutters and these curtains were extended to hang down along the north and south walls. Three black polyethylene curtain heat exchangers were installed within the area enclosed by the overhead curtains. A 9m aluminum pipe 10.2cm in diameter forms the bottom edge of the curtains, which can be rolled up onto the pipes when cords at each end are pulled (see Figure 3).

In the original design for this greenhouse heat was to be obtained from warm water being discharged from the generating station. This water was first utilized in an aquaculture research project and the greenhouse was piped to receive 150 l/min. at 27-30°C from one of the nursery raceways. The warm water was introduced into one corner of the greenhouse floor and circulated through the floor giving up heat, and then discharged from the floor. The discharge could be pumped directly to a drain or to an evaporative pad cooling system. The purpose of this system was to test the concept of using the warm water discharge for evaporative cooling of the greenhouse and to investigate the possibility of providing the generating station with the capacity to cool discharge water by utilizing the wet pad system continuously and independently of greenhouse cooling requirements.

A 7.3m x 1.5m shed was constructed along the west wall of the greenhouse, housing the evaporative cooling system. A perforated pipe distributes water to a pad made up of CELdek cellulose fill. The pad is 7m long, 1.8 m high, and 0.30m thick. A concrete gutter underneath the CELdek drains water to a nearby pond. Air is drawn into a plenum along the west side of the shed, through the pad, and exhausted by two fans in the east wall of the shed. This air either goes directly back into the environment, or some or all of it may be drawn into the greenhouse, depending on the opening of the greenhouse vent window (see Figure 4).

A pump in the northeast corner of the greenhouse provides water to the vertical curtain heat exchanger distribution pipes at the rate of approximately 4.0 l/min per meter of curtain length. The supply of warm water from the aquaculture project was not always reliable due to fluctuations in temperature or complete outages of the supply. Therefore, to enable reliable data to be obtained a backup heating system was required. In order to heat the water in the floor and maintain a uniform temperature in this water, a pump in the southwest corner of the greenhouse circulates water through a 24kW heater to the northeast corner of the greenhouse.

EXPERIMENTAL DESIGN

A primary objective of this investigation was the determination of heat transfer rates from the porous concrete floor, the vertical curtain heat exchangers, and the insulated greenhouse. Energy usage was determined by multiplying the amount of time heaters were on during a specified period by the known wattages of the heater elements. Wattmeters on two of the heater elements served as checks on calculated energy consumption. All evaluations of heat transfer were based on data collected between the hours of 12:00 midnight and 6:00 A.M. Data was recorded over 4 or more hours and tests were conducted with the insulating curtains closed. The thermostat on the water heater was set to maintain water temperatures ranging from 27°C to 30°C. Tests on the vertical curtain heat exchangers were performed with water supply temperatures of approximately 30°C and 35°C. For each test inlet and outlet water temperatures, greenhouse air temperature, and water flow rate were measured.

On numerous occasions during all seasons of the year, the following data on the evaporative cooling system were recorded with the use of a sling psychrometer, a 24-point temperature recorder, and a flow meter: wet and dry bulb air temperatures at the inlet and outlet, inlet and outlet water temperatures, and water flow rate.

Temperatures in the greenhouse, soil, floor water and evaporative cooling system were monitored continuously using copper-constantan thermocouples in conjuction with a 24-point strip chart recorder. Water flow rates were measured with impeller driven meters, and event recorders and elapsed time indicators monitored heater operation, curtain closing and opening, ventilation system performance, and vertical curtain heat exchanger pump operation.

RESULTS

The data pertaining to the calculation of U values through the greenhouse walls based on a total surface area of $270m^2$ is presented in Table 1. All tests were conducted with the overhead curtains closed, but the results for 3/20/79 and 10/18/79 clearly illustrate the effects of tears in the curtains and improper sealing at some of the edges. The other four tests are representative of overall U values that might be expected for an insulated greenhouse and are consistent with the values of 2.6 W/m^2K reported by Simpkins et al. (1979) and 2.8 W/m^2K measured by Mears et al. (1979). Upon examination of the greenhouse geometry and size and giving consideration to the fact that there are many corners and edges that cannot be completely sealed against air currents, one may expect U values higher than might be found in considerably larger greenhouses. However, the decreased thermal resistance of the curtain due to leakage is compensated for by the fact that in the prototype greenhouse the area of the curtains is only about 2/3 of the greenhouse surface area.

The data on the thermal performance of the porous concrete floor is also presented in Table 1. A number of factors significantly affect the thermal characteristics of the floor. The amount of energy transferred by radiation is affected by the size of the crop, the attic temperature, the floor water temperature, and whether or not the vertical curtains are operating. Crop size and type also affect convective heat transfer from the floor, as do the degree to which the overhead curtains are sealed and operation of the vertical curtains. The level of water in the floor and relative humidity in the greenhouse also influence the heat transfer rate. Based on the observed data, a value of U of 7.0 W/m^2K would appear to be a reasonable, conservative estimate of the heat transfer rate from an exposed porous concrete floor with normal greenhouse air temperatures and water temperatures expected from a closed cycle power plant condenser discharge.

The results from the vertical curtain heat exchanger tests are shown in Table 2 and Table 3. Since all tests were conducted during a single three hour period, changing conditions in the greenhouse environment did not significantly affect the results. The graph of U as a function of water flow rate in Figure 6 indicates that the water flow rate does have a significant effect on heat transfer. This is to be expected, since at higher flow rates there is generally a more even distribution of water throughout the curtains. Presumably at a sufficiently high water flow rate the distribution would be so uniform that increases in water flow would not continue to affect the heat transfer rate.

The information collected on the evaporative cooling system is tabulated in Table 4. In the absence of a suitable model that might predict system performance based on the measured parameters an attempt was made to develop an empirical model. A multiple regression was performed on the cooling system data to attempt to correlate the outlet conditions to inlet parameters. For purposes of analysis the air and water flow rate were taken to be independent variables, whereas the outlet conditions were considered dependent. An examination of the regression analysis using all measured variables indicated that the performance of the cooling system might be adequately modeled using only the inlet wet bulb temperature (t_{wb}) and the water inlet temperature (t_w). This hypothesis is confirmed by the high coefficients of correlation obtained in the regression analyses using only t_{wb} and t_w as independent variables. The resulting model and coefficients of correlation are shown in Table 5. The data presented and analyzed here on the performance of the evaporative pad system are all taken from warmer months when greenhouse cooling might be required. In the winter and cooler periods of spring and fall there would be no need for greenhouse cooling but the system was run continuously in order to evaluate the potential for water cooling. It was found that under cool air conditions there is substantial water cooling at all times. If air inlet wet bulb was less than 10°C then water cooling was more than 10°C. If the air inlet wet bulb is below freezing the water temperature will approach freezing.

CONCLUSIONS

The insulating curtains were quite effective at reducing greenhouse heat loss, resulting in about 30% lower energy requirements when compared to the uninsulated greenhouse. The overhead curtain system could be used for photoperiod control, and the drive system is potentially useful for reducing the summertime cooling load if the insulating curtains could be replaced by a shading material.

The vertical curtain heat exchangers have been shown to be an extremely good system for distributing heat to the greenhouse from low temperature water at very low cost. However, there is a significant problem in locating these curtains within the greenhouse so that there is a minimum of shading of plants and at the same time no interference with greenhouse operations and plant growth.

The thermal properties of the porous concrete floor which enable it to be used as a primary heat source for the greenhouse, combined with other advantages such a system might have in a commercial greenhouse operation, such as weed control, the elimination of water puddling on greenhouse floors, and a surface that will support light vehicular traffic, make this type of floor an attractive option for making use of power plant waste heat. The floor also provides an elevated, uniform temperature at the greenhouse floor that can be of considerable benefit to some crops.

The CELdek evaporative pads performed with a minimum of problems, and proved to be quite adequate at cooling both water and warm air. Although the water flowing through the pads was at times heavily silted, relatively little fouling of the pads occured, and over a six month period of continuous use no change was noticed in the performance of the pads. During extremely cold weather the area around the air intake into the cooling system accumulated considerable amounts of ice and air flow was somewhat restricted, although the water running through the CELdek continued to be substantially cooled. The design of the shed housing the evaporative cooling system does not appear to be ideal, and may have contributed to somewhat nonuniform flow through the pads, restriction of air flow, and, to some degree, the problem of icing in cold weather. Ice accumulation can also be reduced by drawing less air through the pads in cold weather.

FURTHER WORK

The research reported on here has been useful in determining the heat transfer coefficients and system component performance needed to design a full scale prototype system. In companion research a 0.54 hectare commercial greenhouse has been operated with a similar floor heating system for more than two complete growing seasons(Mears *et al.*,1979). In these programs it has been demonstrated that a variety of crops can be produced with this heating system and that floor heating provides definite cultural advantages for many crops. A great deal needs to be done in order to determine the best cultural practices to most fully exploit the potential advantages of this type of heating system. A full scale prototype incorporating these concepts needs to be constructed and tested using actual power plant cooling discharge water to determine what problems there may be that do not show up in a small research unit and to learn what economies of scale can be acheived when working in a full scale commercial unit.

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GREENHOUSE AND FLOOR HEAT TRANSFER DATA

DATE	AVG FLOOR TEMPERATURE	AVG GHSE TEMPERATURE	AVG OUTSIDE TEMPERATURE	AVG POWER CONSUMPTION	U CONCRETE FLOOR	U GREENHOUSE WALLS
	°C	°C	°C	Watts	W/M^2K	W/M^2K
3/12/79	27.2	8.3	-5.0	9,000	7.8	2.5
3/15/79	27.2	9.4	-1.7	8,200	7.5	2.7
3/20/79	26.1	10.0	2.2	6,850	6.9	3.2
9/25/79	29.4	18.0	11.1	4,660	7.3	2.5
10/18/79	30.0	16.7	11.1	5,620	7.5	3.7
11/13/79	30.0	16.1	7.8	6,200	8.0	2.7

Exposed Floor Area = $A_{fl} = 56m^2$

Greenhouse Surface Area = $A_{gh} = 270m^2$

Table 1

NORTH VERTICAL CURTAIN DATA

FLOW RATE L/min.	GREENHOUSE TEMPERATURE ^{o}C	AVG WATER TEMPERATURE ^{o}C	POWER OUTPUT Watts	U VERTICAL CURTAINS W/M^2K
15.1	16.7	31.8	4,625	6.6
15.1	16.7	32.6	4,100	5.6
15.1	17.2	32.6	4,730	6.6
26.9	17.2	33.6	5,805	7.6
37.9	17.2	34.0	6,068	7.8
39.4	17.2	34.0	5,760	7.4
39.4	16.7	34.1	6,034	7.5
40.5	16.7	34.3	6,484	8.0
55.3	16.7	34.2	7,315	9.0
15.1	16.7	28.8	3,154	5.6
37.9	17.2	29.5	3,958	7.0

Total Surface Area, $A = 46.3m^2$

Table 2

SOUTH VERTICAL CURTAIN DATA

FLOW RATE L/min.	GREENHOUSE TEMPERATURE °C	AVG WATER TEMPERATURE °C	POWER OUTPUT Watts	U VERTICAL CURTAINS W/M^2K
29.6	17.2	33.6	5,431	7.2
27.6	17.2	33.5	5,380	7.2
37.9	16.7	34.2	6,333	7.9
39.0	16.7	32.9	6,245	8.4
39.0	17.2	34.0	5,702	7.4
39.0	16.7	34.0	6,516	8.2
40.0	17.2	34.0	5,980	7.7
56.8	17.8	34.0	6,726	9.0
64.8	17.2	34.5	6,767	8.6
27.6	16.7	29.2	4,035	7.0
40.9	17.2	29.5	4,271	7.6

Total Surface Area, A = $45.8m^2$

Table 3

EVAPORATIVE COOLING SYSTEM DATA

DATE	INLET DRY BULB °C	INLET WET BULB °C	EXHAUST DRY BULB °C	EXHAUST WET BULB °C	WATER INLET °C	WATER OUTLET °C	FLOW RATE L/min.	WATER ΔT °C
08/24/78	32.2	22.8	25.0	23.9	29.8	24.4	166.8	4.4
09/15/78	26.7	20.8	23.9	23.3	26.7	22.2	178.1	4.4
09/07/78	29.4	22.2	25.0	23.9	26.7	23.9	172.8	2.8
09/11/78	26.7	21.7	23.3	21.1	25.6	22.8	172.8	2.8
09/12/78	29.4	22.8	24.4	23.9	26.1	23.4	173.6	2.7
09/13/78	21.7	14.7	18.1	17.8	25.6	17.4	173.2	8.1
09/20/78	23.9	18.1	20.3	19.4	23.3	18.2	90.6	5.1
09/26/78	17.8	11.7	15.0	15.0	22.8	15.2	130.4	7.6
10/11/78	23.3	15.8	18.9	18.9	23.3	17.9	127.3	5.4
10/16/78	13.3	7.8	13.3	12.5	22.2	12.2	98.2	10.0
10/23/78	25.3	16.4	19.4	18.9	21.1	17.6	163.7	3.6
07/13/79	33.3	23.9	24.4	23.3	26.4	24.4	155.4	1.9
07/14/79	35.0	22.8	24.7	23.3	27.8	24.4	155.4	3.3
07/15/79	33.3	22.8	24.4	23.3	26.7	23.3	155.4	3.3
07/24/79	29.4	25.0	26.4	25.6	28.9	25.6	151.6	3.4
07/27/79	28.9	22.2	25.6	24.4	30.0	23.3	151.6	6.7
07/31/79	29.4	25.0	26.4	25.8	29.4	25.6	125.1	3.9
08/02/79	29.4	25.6	27.8	26.9	31.7	26.1	128.9	5.6
08/17/79	21.7	15.3	17.8	15.8	21.1	15.6	128.9	5.6
08/21/79	25.0	19.7	21.1	20.0	21.7	19.4	113.7	2.2
08/23/79	26.4	20.0	21.9	20.3	21.1	20.0	113.7	1.1
08/28/79	27.2	22.7	25.0	24.2	27.8	23.3	100.1	4.4
09/03/79	26.7	23.3	24.4	23.9	27.2	23.3	105.0	3.9
09/10/79	23.9	16.9	19.4	18.1	21.7	17.8	108.0	3.9
09/13/79	23.1	18.3	20.6	19.4	22.2	18.9	115.2	3.3
09/16/79	23.3	16.4	18.3	17.2	22.2	17.2	112.6	5.0
09/17/79	23.3	16.4	18.3	17.2	22.2	18.3	111.8	3.9
09/20/79	19.4	11.9	15.3	14.4	21.1	15.0	126.2	6.1
09/24/79	17.8	13.9	15.8	15.3	19.4	15.3	113.7	4.2
09/25/79	18.6	15.8	16.9	16.7	18.3	15.7	113.7	2.7
09/27/79	20.3	16.4	17.8	17.2	19.4	16.9	113.7	2.6
09/28/79	22.8	18.6	20.0	19.4	20.0	19.2	115.6	0.8

Table 4

EVAPORATIVE COOLING SYSTEM PERFORMANCE - REGRESSION MODEL

$$t'_{db} = 1.43 + 0.71t_{wb} + 0.26t_w \qquad R^2 = 0.985$$

$$t'_{wb} = 0.66 + 0.67t_{wb} + 0.29t_w \qquad R^2 = 0.979$$

$$t'_w = 0.25 + 0.67t_{wb} + 0.30t_w \qquad R^2 = 0.983$$

Where: t_{wb} = inlet air wet bulb temperature

t_w = inlet water temperature

t'_{db} = outlet air dry bulb temperature

t'_{wb} = outlet air wet bulb temperature

t'_w = outlet water temperature

Table 5

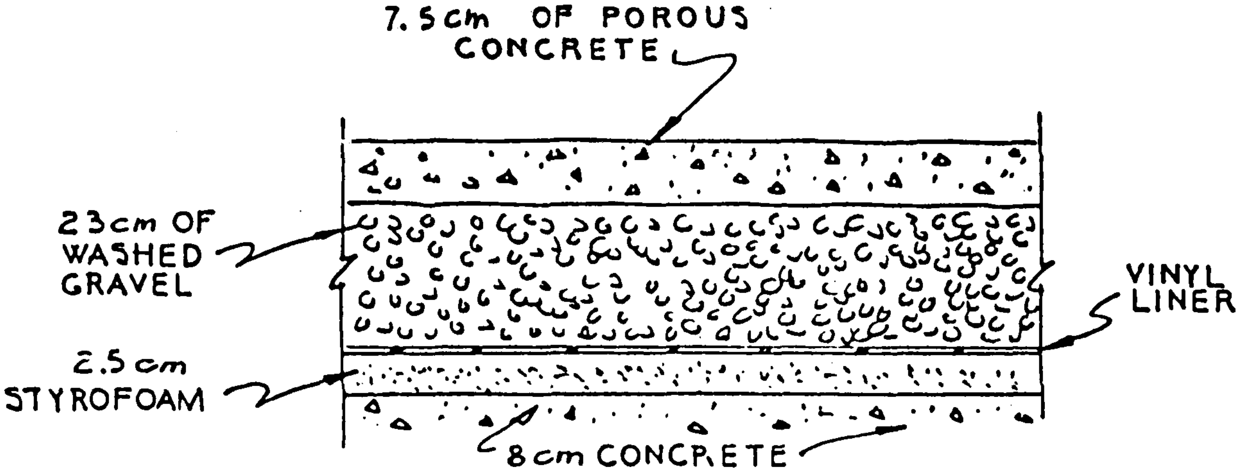

FIG. 1 POROUS CONCRETE FLOOR CROSS SECTION

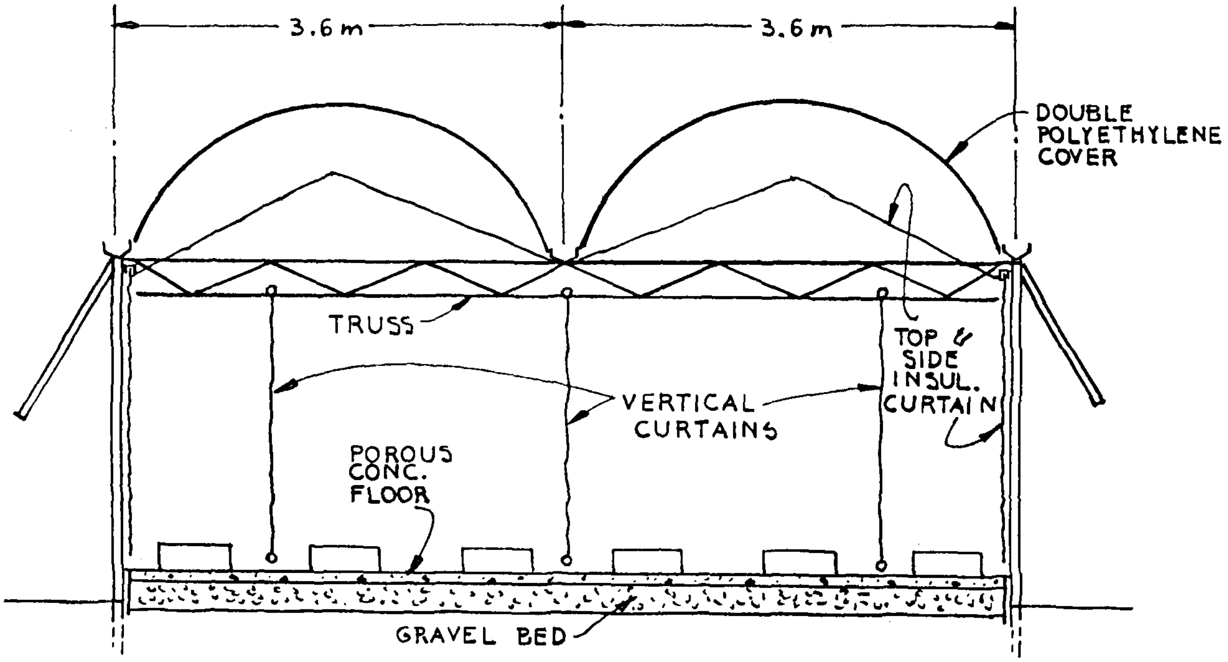

FIG. 2 GREENHOUSE CROSS-SECTION

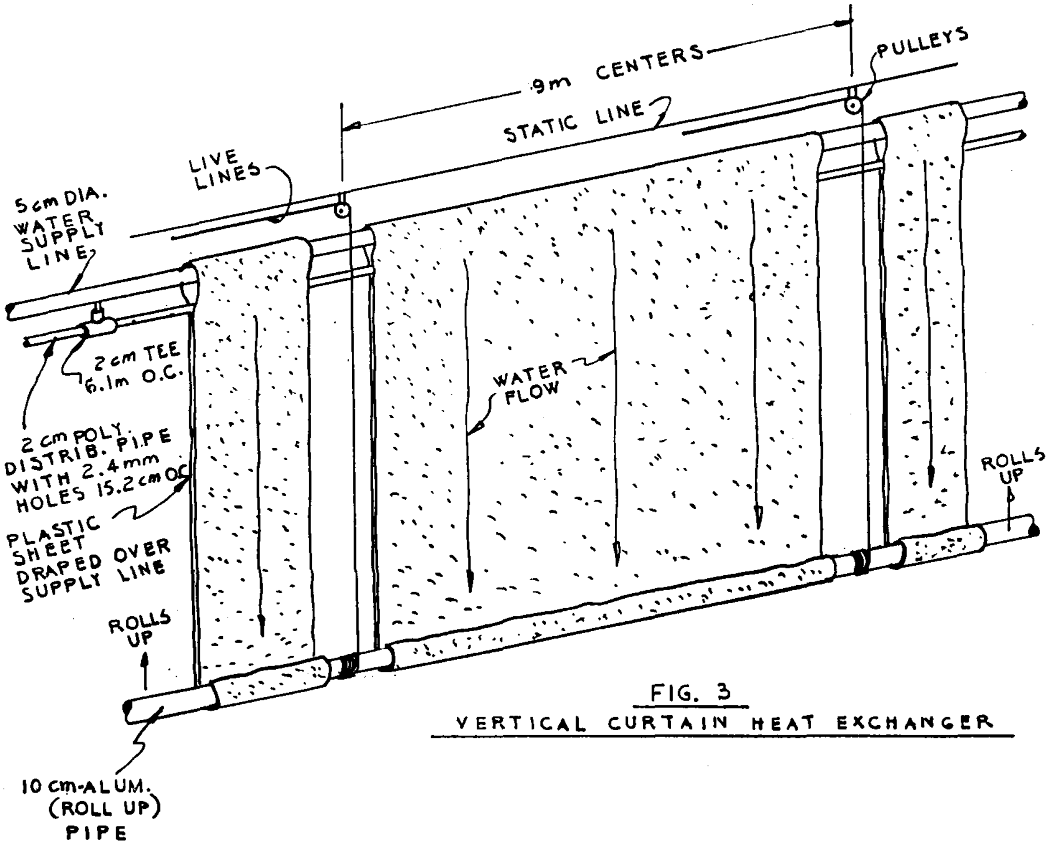

FIG. 3
VERTICAL CURTAIN HEAT EXCHANGER

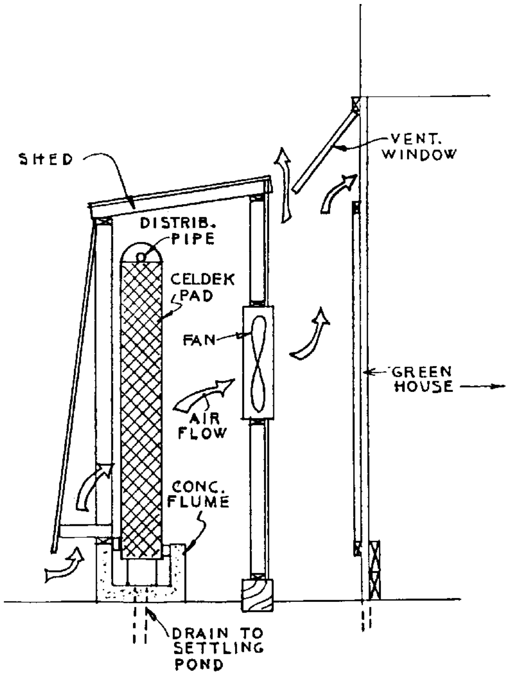

FIG. 4 EVAPORATIVE COOLING SYSTEM

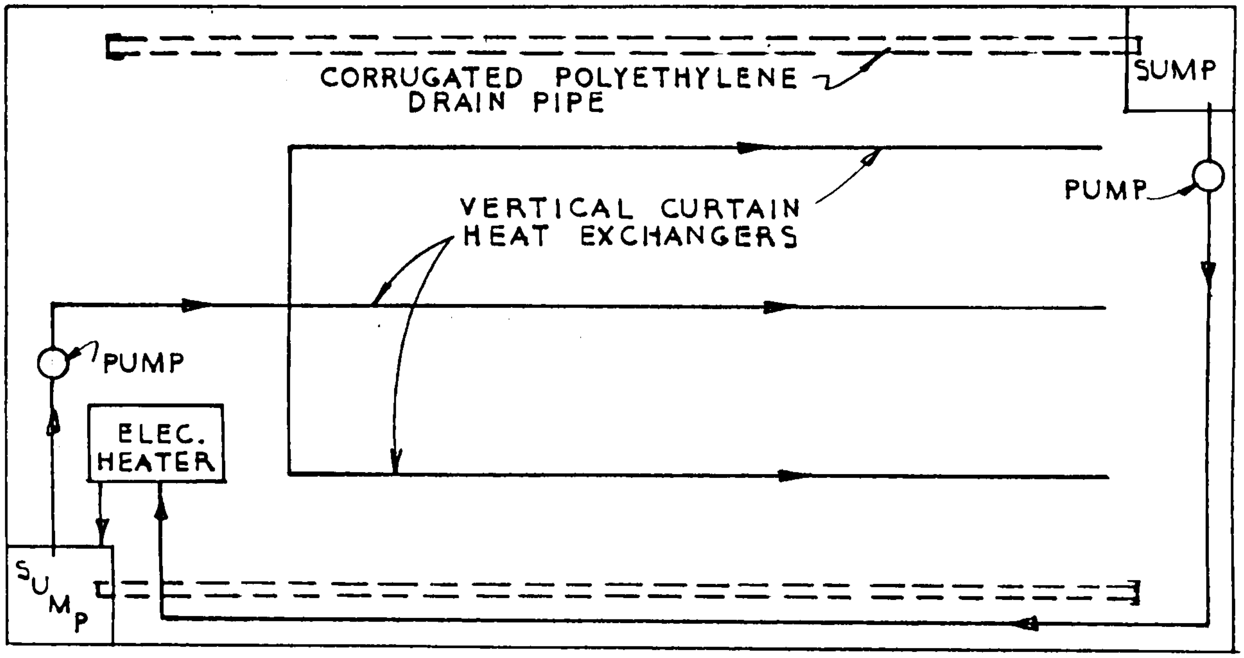

FIG. 5 SCHEMATIC DIAGRAM OF BACK UP HEATING SYSTEM TO MAINTAIN AIR TEMPERATURE