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ENGINEERING PERFORMANCE OF A 1.1 HECTARE WASTE-HEATED GREENHOUSE

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SUMMARY:

Data for an entire heating season was collected from a 1.1 hectare greenhouse in Washingtonville, Pennsylvania, which uses condenser discharge water from the Pennsylvania Power and Light Montour County Generating Station as its primary heat source. These data were used to evaluate the heating components and overall thermal performance of the greenhouse.

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Thomas O. Manning, David R. Mears and Martin Buganski*

Introduction:

New greenhouse technologies attempt to reduce costs and maximize production per unit area in order to improve the economic viability of the greenhouse industry. One way to lower energy costs, which represent a significant proportion of greenhouse operating expenses in much of the United States, is to use industrial waste heat. Since the early 1970's several commercial greenhouses have been built that use condenser cooling water from closed-cycle electrical generating stations (Widmer, 1979, Pile _et al.,_ 1978).

In 1980, cooperative efforts between Pennsylvania Power and Light (PP&L), Rutgers University, and Ken Bryfogle (a greenhouse grower), resulted in the construction of a 1.1 hectare greenhouse in Washingtonville, Pennsylvania, using concepts developed during research at Rutgers University on the use of solar and waste heat for greenhouses. This facility uses condenser discharge water from the PP&L Montour County Generating Station to provide most of its heating requirements. From the onset of this project it has been apparent that much could be gained from an increased understanding of the interactions of the heat supply (power plant discharge water), the heat distribution system and the greenhouse environment. Toward this end, collection of data from the Washingtonville greenhouse began in January of 1982. This data will provide a basis for improvements to the heating system and environmental control strategies. This paper is a preliminary report on the results of the first full year of data collection from the Washingtonville greenhouse.

The main design objectives for the Washingtonville greenhouse were to integrate the heating systems into the overall greenhouse design and to use components that complement each other in their operation. The heating systems were based on the results of research conducted at Rutgers University since 1974 that applied basic heat transfer principles to the problem of heating greenhouses with low temperature heat sources. The greenhouse was designed after a number of alternative heating systems were evaluated using computer simulations. Data on thermal properties of the heating components were obtained from the previous greenhouse research at Rutgers University and manufacturers' specifications. Water and outside ambient temperatures used in the simulations were taken from Montour Power Plant operational reports for 1980 and 1981. The final greenhouse design incorporates two warm water distribution systems, two back-up heating systems, and overhead insulating blankets.

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Description of the Washingtonville Greenhouse:

The 1.1 hectare greenhouse consists of twenty gutter-connected 64 x 8.5m bays. The roof glazing is double-layer, air-inflated polyethylene, and the outside walls are covered with ultraviolet-resistant, translucent fiberglass panels. Overhead insulating blankets reduce the heat load and provide photoperiod control or shading.

A flooded floor system is the primary heat exchanger for the greenhouse. It is constructed of a 0.5mm biocide-treated vinyl swimming pool liner filled with 20cm of gravel which is flooded with water and covered with a 7.5cm cap of porous concrete. The water and gravel provide thermal storage and are heated by the condenser discharge water which flows through 64m lengths of 1.9cm polyethylene pipe embedded in the gravel on 35cm centers. Details of the floor are shown in Figure 1. Two 3.2cm finned pipes underneath each gutter serve as secondary heat exchangers for the waste heat (Figure 1). The power plant water is supplied to these two systems by a PVC header, 20cm in diameter and 170m long, along the east wall of the greenhouse. This header connects directly to the 50cm polyethylene pipe from the PP&L cooling tower.

The back-up heating system consists of two boilers, one oil-fired and one fired with either oil or coal. When needed, boiler water may be pumped through a supplementary finned pipe under each gutter (Figure 1). A heat exchanger with 10 loops, each 60m in length, located in a water flume along the west wall of the greenhouse, connected to the boiler, maintains minimum floor water temperatures. The back-up heating system is designed both to supplement the waste heat when the primary and secondary waste heat exchangers cannot provide all the heating requirements and to supply the full greenhouse heat load when no waste heat is available. A 5.2kW pump in the southwest corner of the greenhouse circulates water through the gravel in the floor. A system of 10cm perforated drain pipes in the floor on 3m centers distributes the water flow evenly through the floor (Figure 2).

The greenhouse is used year round to grow various crops, including Easter lilies, poinsettias, mums, geraniums, bedding plants and some hanging basket plants. Four zones allow different crops to be grown at different minimum temperatures.

The data acquisition system at the Washingtonville greenhouse consists of these basic components: a Northstar micro-computer, a Visual 200 display terminal, an Epson MX-80 printer and Burr-Brown multiplexers and Analog to Digital converters*. Two multiplexers receive digital data from 8 remote transmitters, each capable of converting 16 channels of analog information. The micro-computer queries the multiplexers approximately once every thirty seconds, and the data is recorded onto 5 1/4 inch floppy disks at intervals that can be individually programmed for each sensor. This information is also printed to insure against losing all the data during a power failure or as the result of some other problem. The sensors are Copper-Constantan thermocouples, 100 ohm Platinum RTD's and Signet paddlewheel flow sensors. The pulse signal from the flow sensor is converted to a 4-20ma signal by a Signet Signal Converter. The location of thermocouples for measuring air temperatures is shown in Figure 1, and other sensor locations are shown in Figures 2-4.

* Reference to commercial products is made with the understanding that no discrimination and/or endorsment is intended or implied.

Results:

The greenhouse floor is the most important component of the greenhouse heating system and the most difficult to evaluate. Waste heat is introduced into the floor via a network of polyethylene pipes. The energy input to the floor in each of the four greenhouse zones is calculated based on the temperature of the water in the main supply. The flow rate and temperature are measured in the 7.5cm pipe that discharges into the main return pipe as shown in Figure 3. The back-up boilers can be used to heat the floor water with the heat exchanger in the flume along the west wall of the greenhouse. The energy flows in this exchanger are based on measurements of temperatures in the supply and return pipes and the flow in the return pipe (Figure 2).

The most important design parameter for this type of floor is the effective heat transfer rate (U) between the warm water in the pipes and the greenhouse air. However, because of the considerable thermal mass of the floor, at any one time the heat transferred to the greenhouse air from the floor is not the same as the heat transferred to the floor from the water in the pipes. Furthermore, the floor is not homogeneous, and it is very difficult to establish a representative floor water temperature. Water temperatures differ from one side of the greenhouse to the other as well as being subject to local variations such as might be the case in water surrounding one of the pipes in the floor. This problem is compounded in the Washingtonville greenhouse by the fact that the floor surface elevations, and, consequently, the floor water levels, deviate by as much as 15cm. After many unsuccessful attempts to measure a representative water temperature, late in the heating season a thermocouple was placed in the outlet of a small pump with its intake embedded in the floor, effectively creating an "aspirated" floor water sensor which averages local temperature variations. This appears to be the most reliable way to measure floor water temperature.

One means of estimating the heat transfer rate from the power plant water to the greenhouse air is to compare, over a period of several days, the energy input into the floor to the temperature difference between the water in the pipes and the greenhouse air in order to average out the effect of the thermal mass of the floor. Analysis of data from January through March 1983 using this method yields values for U that range from 2.5 to 3.7W/m^{2}K.

Another means of estimating U for the floor system is to compare the average temperature difference between the water in the pipes and the greenhouse air to that between the free water in the floor and the greenhouse air. The effective U can then be expressed as a fraction of the U from the free water to the air, a value which has been measured numerous times in similar greenhouse floors and ranges from 6.9 to 8.0W/m^{2}K (Roberts et al., 1980, Manning et al., 1980). Figure 5 is an illustration of these temperature differences, using water temperatures measured in the center of the greenhouse. Based on these data, the average water temperature in the pipes was 32.9°C, the average water temperature was 25.2°C and the average air temperature was 14.2°C. This suggests that the effective U for pipe water temperatures of about 30°C is approximately (25.2-14.2)/(32.9-14.2) or .6 times previously measured values of U. This translates to values of U from 4.1 to 4.8W/m^{2}K for the Washingtonville greenhouse.

The results of these two methods for calculating heat transfer for the flooded floor are clearly contradictory, and the values for U are significantly less than had been expected based on previous experience. The fact that the U calculated using the second method is higher than that determined by the first suggests that the heat transfer rate based on the temperature of the free water is actually lower than $6.9 W/m^2K$. One probable cause for this discrepancy is that the water level in the gravel is, on average, well below the bottom of the porous concrete due to the variation in the level of the floor. As a result, heat has to move through a layer of gravel and air where heat conduction is quite low. A ratio of 0.6 of effective U to the U from the water to the air is also lower than had been anticipated. This may also be caused by low water levels, which reduce heat transfer from the polyethylene pipes because they are not fully immersed or because the lower thermal mass results in higher sink (water) temperatures which decrease the average temperature difference between the water inside and outside the pipe. Different types of crops also affect the heat transfer of the floor, and bedding plants grown in flats during the spring probablyhave caused some of the reduction in floor heat transfer. The data concerning energy flows in the floor will be studied in more detail to clarify the causes of the unexpectedly low heat transfer rates, and to further understand how heat is transferred from the water to the air, a process which is not fully understood at present.

The heat transfer from finned pipe in the greenhouse was measured in the overhead waste heat and boiler back-up pipe loops. The locations of sensors for the waste heat distribution and back-up pipe loops are shown in Figures 3 and 4 respectively. The equation for predicting heat transfer from finned pipe is $Q = c(t_w-t_a)^n$ where t_w is the water temperature in the pipe, t_a is the air temperature, n is a property of the pipe, and c is an empirically determined coefficient. The manufacturer's specifications for the finned pipe used in Washingtonville conform to the equation $Q = 3.40(t_w-t_a)^{1.4}$ where temperatures are in degrees Celsius and Q is in watts per meter. As shown in Figure 6, the measured heat transfer was somewhat lower than the manufacturer's figures, and the best fit to the data retaining a value of 1.4 for n results in a coefficient of 2.46, or $Q = 2.46(t_w-t_a)^{1.4}$. This reduction is attributed to the proximity of the pipes to each other as well as to other objects that could interfere with convective air flow, including the insulating blankets. The data shown in Figure 6 reflect energy flow measurements in the waste heat finned pipe network and in the pipes connected to the back-up boiler. The deviation of observed data from both curves at low temperature differences is most likely due to the large measurement error in this range and the fact that air around the pipe is somewhat colder than it is at the plant canopy where air temperature was measured.

Energy input to the heat exchanger was measured using sensors placed as illustrated by Figure 2. The temperature of the water in the flume entering the heat exchanger was calculated by averaging the temperatures measured at four locations in the gravel along the western edge of the greenhouse floor. A thermocouple in the sump in the southwest corner of the greenhouse measures the temperature of the flume water at the heat exchanger exit. The pump in this corner is always operating when the heat exchanger is on in order to circulate the heat through the floor, so the water in this sump is well mixed. The UA for this heat exchanger was computed by dividing the energy input by the log mean temperature difference between the water inside the heat exchanger and the water in the flume. The average UA over a range of temperatures was determined to be 15,200W/K, which corresponds to a U of 126 W/m^2K based on a pipe surface area of $119m^2$. The heat exchanger is therefore capable of maintaining floor water temperatures at 30°C when the greenhouse temperature is 18°C, which was the design objective. Figure 7 is a plot of the heat exchanger performance data.

The thermal curtains are made from a woven material which permits some air movement through the curtain. The energy savings due to the curtains were estimated by comparing the temperature difference between the air above the curtain and the outside ambient air to that between the air below the curtain and the air outside. Based on data recorded on three nights when the outside temperature was below 0°C and the back-up heat was not running, energy requirements with the blanket closed were approximately 2/3 of those of the uninsulated greenhouse. Based on a U of $4.5W/m^2K$ for a gutter-connected, double-layer polyethylene greenhouse, the corresponding U is $3.0W/m^2K$.

When water circulates in the overhead back-up heating pipes, the insulating value of the curtains changes dramatically. Hot air passing over the finned tube apparently rises through the curtain, and, on the average, the air above the curtain may actually be warmer than the air below it. Therefore, when the overhead back-up heating system is operating the curtains may be of little or no use. This is not only because the curtain is permeable to air, but also because the finned pipe is close to the curtain, and contains water at temperatures up to 80°C. The transfer of as much as 700W per meter of pipe induces strong convective currents which can move heated air through the curtain.

Table I
PROJECTED ENERGY CONSUMPTION PER HECTARE

	ENERGY USAGE (MW-hr)						
Month	Floor Back-up	Floor Waste Heat	Overhead Waste Heat	Overhead Back-up	TOTAL	% Back-up	% Waste Heat
October	10.0	218.2	141.5	0.3	370.0	2.8	97.2
November	0.1	308.6	252.4	1.7	562.8	0.3	99.7
December	0.1	329.1	275.2	6.7	611.1	1.1	98.9
January	43.5	205.5	134.7	90.9	474.6	28.3	71.7
February	11.3	196.6	171.1	121.9	500.9	26.6	73.4
March	8.4	241.5	118.6	14.9	383.4	6.1	93.9
April	182.2	0.0	0.0	136.9	319.1	100.0	0.0
TOTAL	255.6	1499.5	1093.5	373.3	3221.9	19.5	80.5

Energy flows in two of the four heating zones in the greenhouse were summed over the period from October 1982 through April 1983, and projected for a one hectare greenhouse. The results are tabulated in Table I and plotted in Figure 8. The total energy usage of 3200MW-hr is roughly what is expected for a one hectare greenhouse with thermal blankets in Washingtonville. However, the decrease of energy from waste heat in December through March as compared to November and December is somewhat unexpected since waste heat flow is dependent primarily on the temperature difference between the power plant water and the greenhouse air. This situation may be due to a combination of lower incoming water temperatures, low water levels in the floor, and reduced flow in the waste heat distribution pipes. In April, 1983, the generating unit that supplies the greenhouse with water was shut down for routine maintenance; consequently all the heat for April came from the back-up system.

Conclusions:

Table II is a comparison of the values used in designing the Washingtonville greenhouse (Manning and Mears, 1981) and those calculated from the data recorded between October 1982 and April 1983. Although the amount of back-up heat used was greater than had been anticipated, the amount of fossil fuel actually used is still very low. In spite of the fact that floor heat transfer is unlikely to reach expected values, since the problem is most probably caused by the variation in elevation of the floor, back-up energy requirements can be reduced by improved control mechanisms. With the exception of pumps for the overhead back-up heating system and the thermal curtains, all the greenhouse heating components are manually controlled. Manual control of the heat exchanger for the floor creates the most serious problems. Because of the difficulty of measuring water temperature in the floor, water temperatures in some parts of the floor can be as high as 35°C when the heat exchanger is operating. Controlling the heat exchanger based on an average floor water temperature and modulating the temperature of the water in the heat exchanger pipes will solve this problem and create more uniform floor temperatures. Modulating the water temperature in the back-up overhead pipe loops based on greenhouse air temperature will help solve the problem of heated air by-passing the thermal curtains and prevent the back-up heating system from overshooting the thermostat setting. Implementing these changes should reduce the fossil fuel requirements to ten percent or less of the total energy needs. Future fossil fuel requirements for the Washingtonville greenhouse should be lower in any case since the second generating unit of the power plant will be connected to the greenhouse pipeline by fall, 1983, so waste heat should be available more than 95% of the time.

Table II
COMPARISON OF DESIGN AND MEASURED PARAMETERS

	Design	Measured
Greenhouse heat transfer	3.1 W/m^2K*	3.0 W/m^2K*
Effective floor heat transfer	5.1 W/m^2K	2.5-3.7 W/m^2K
Finned pipe heat transfer	230 W/m**	172 W/m**
Energy supplied by waste heat	97 %	81 %

*When back-up heat is off, based on uninsulated $U = 4.5 W/m^2K$
** Based on water at 50°C and air at 18°C

Future Work:

Data collection at the Washingtonville greenhouse will continue through spring of 1984. Additional sensors and solar radiation measurements will provide an even more complete picture of its thermal performance. The data that has been collected so far will be analyzed further to provide more information about the deviations from expected results and investigate thermal performance during differing environmental conditions. Recommendations for automation of greenhouse control will also be made on the basis of this data. The back-up heating system will be altered to provide better temperature control and reduce back-up heating requirements.

Acknowledgements:

The authors wish to thank Kenneth Bryfogle and the employees of Power Plants Inc. for their assistance in maintaining and debugging the data acquisition system. The continued support of Pennsylvania Power and Light is also greatly appreciated.

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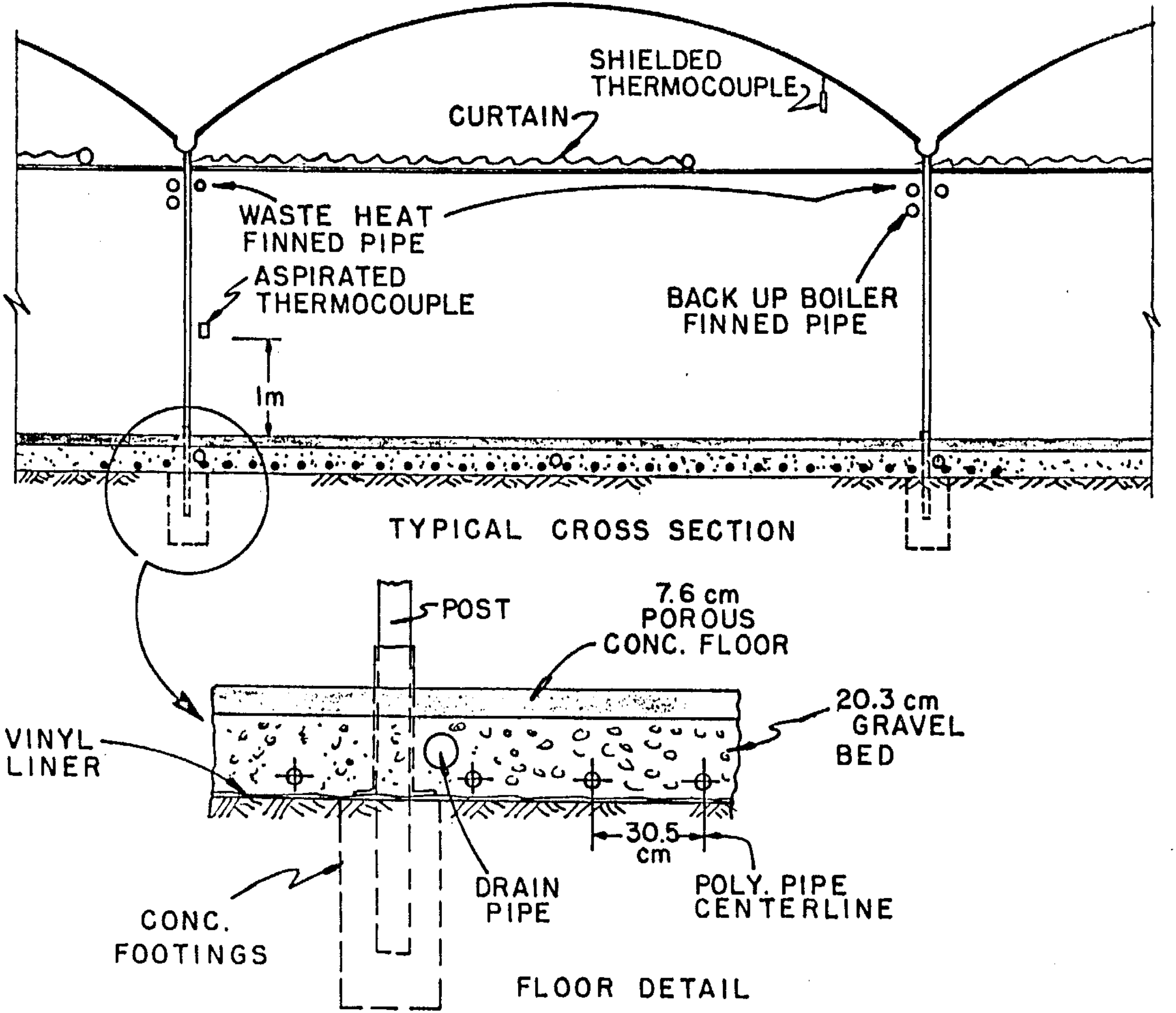
5. Widmer, R.E. 1979. Commercial greenhouse heating with reject heat from electrical generating plants. HortScience 14(5):556,675.



TYPICAL CROSS SECTION

FLOOR DETAIL

Fig 1

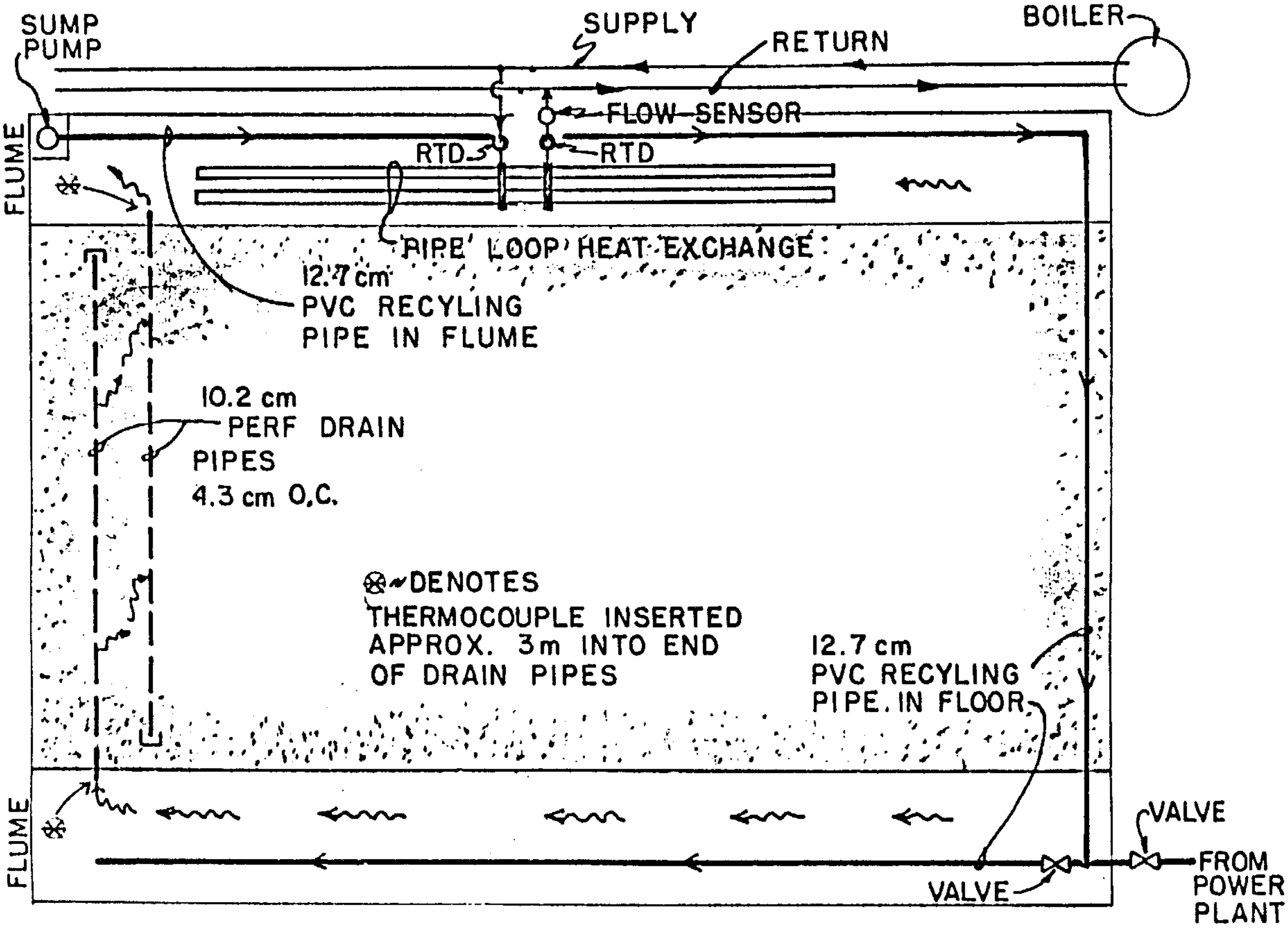


Fig. 2 BACK-UP FLOOR HEATING SYSTEM

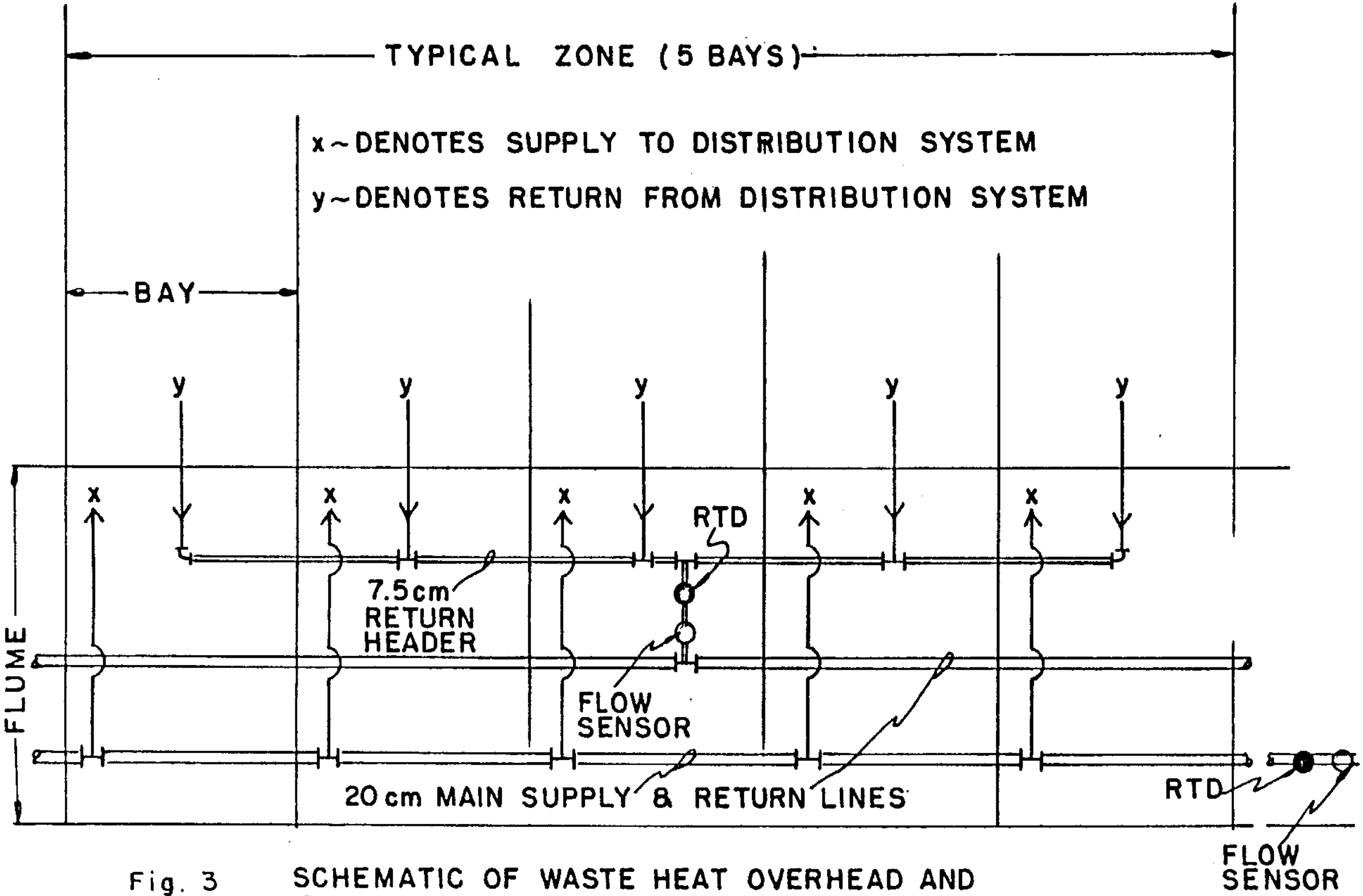


Fig. 3 SCHEMATIC OF WASTE HEAT OVERHEAD AND FLOOR DISTRIBUTION SYSTEM

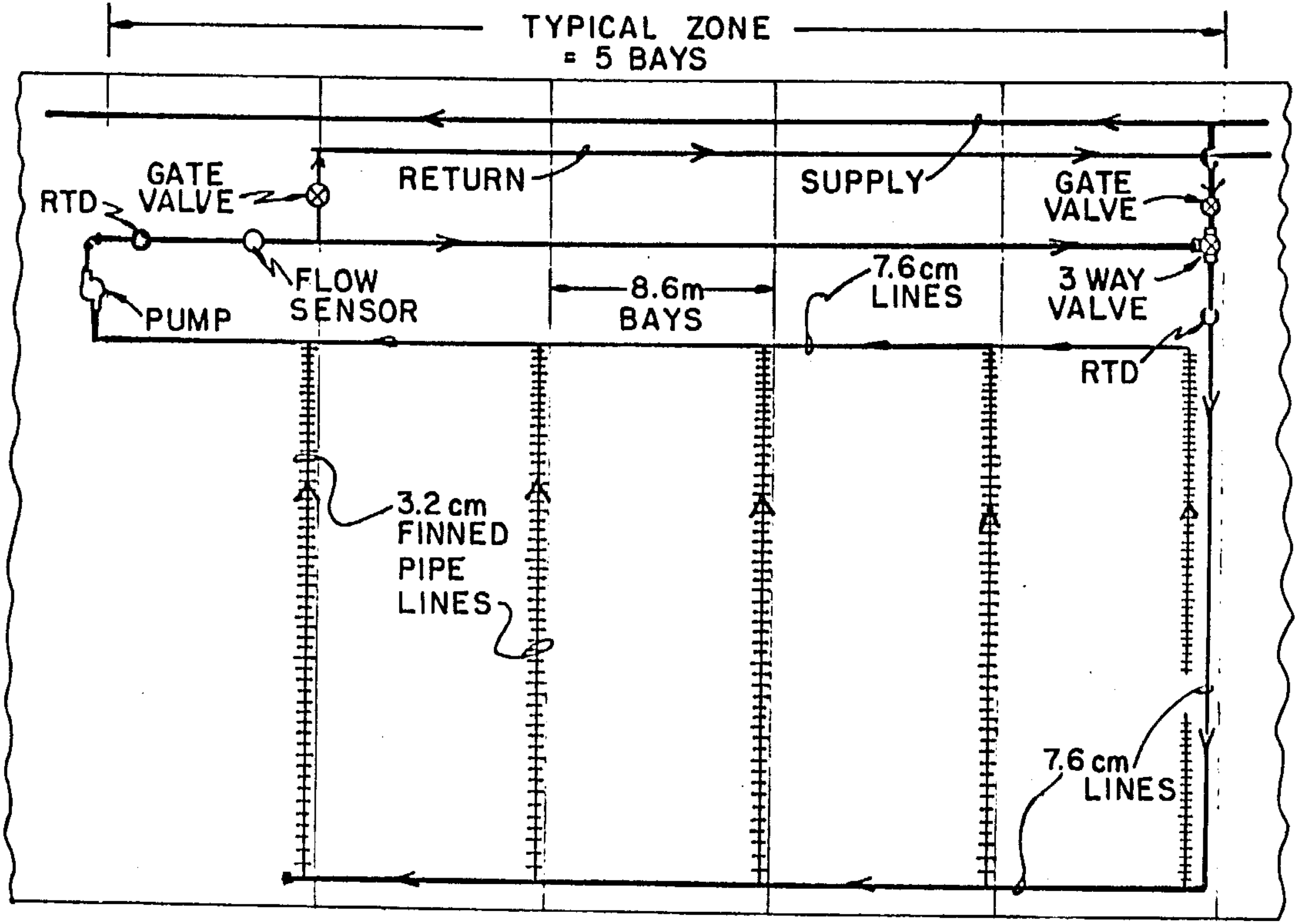


Fig.4 BACK-UP OVERHEAD PIPE HEAT SYSTEM

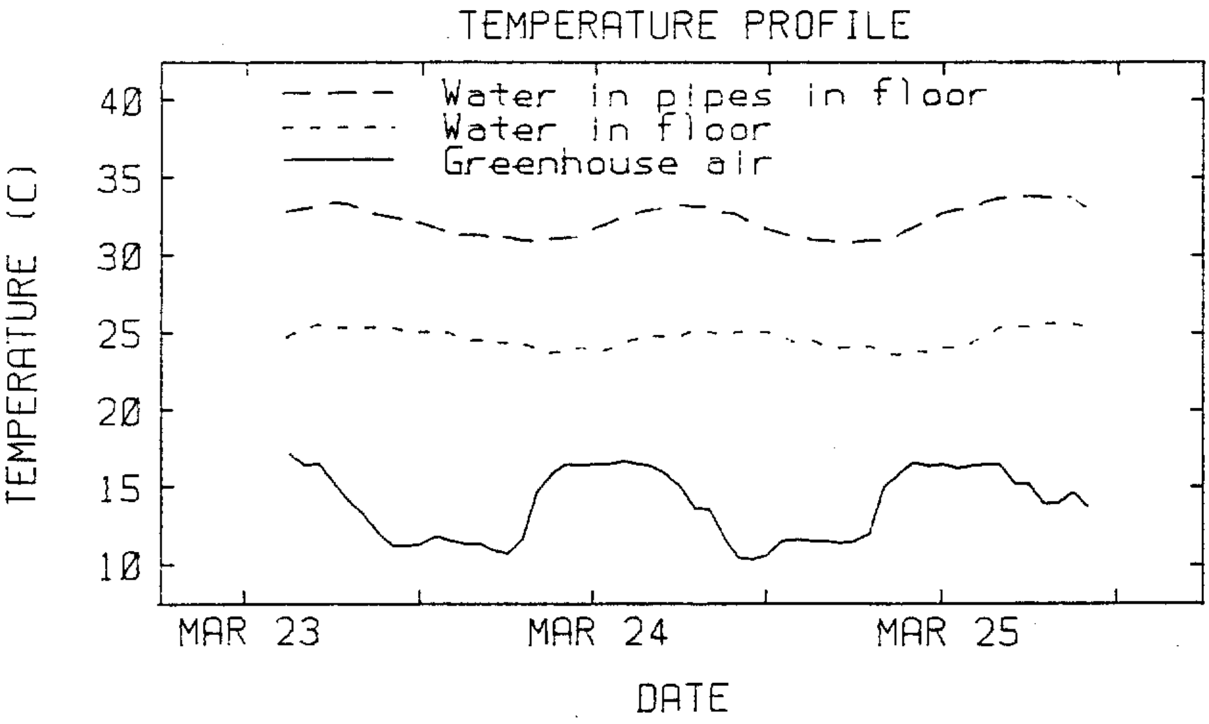

TEMPERATURE PROFILE
Water in pipes in floor
Water in floor
Greenhouse air
TEMPERATURE (C)
40
35
30
25
20
15
10
MAR 23
MAR 24
MAR 25
DATE

Fig. 5

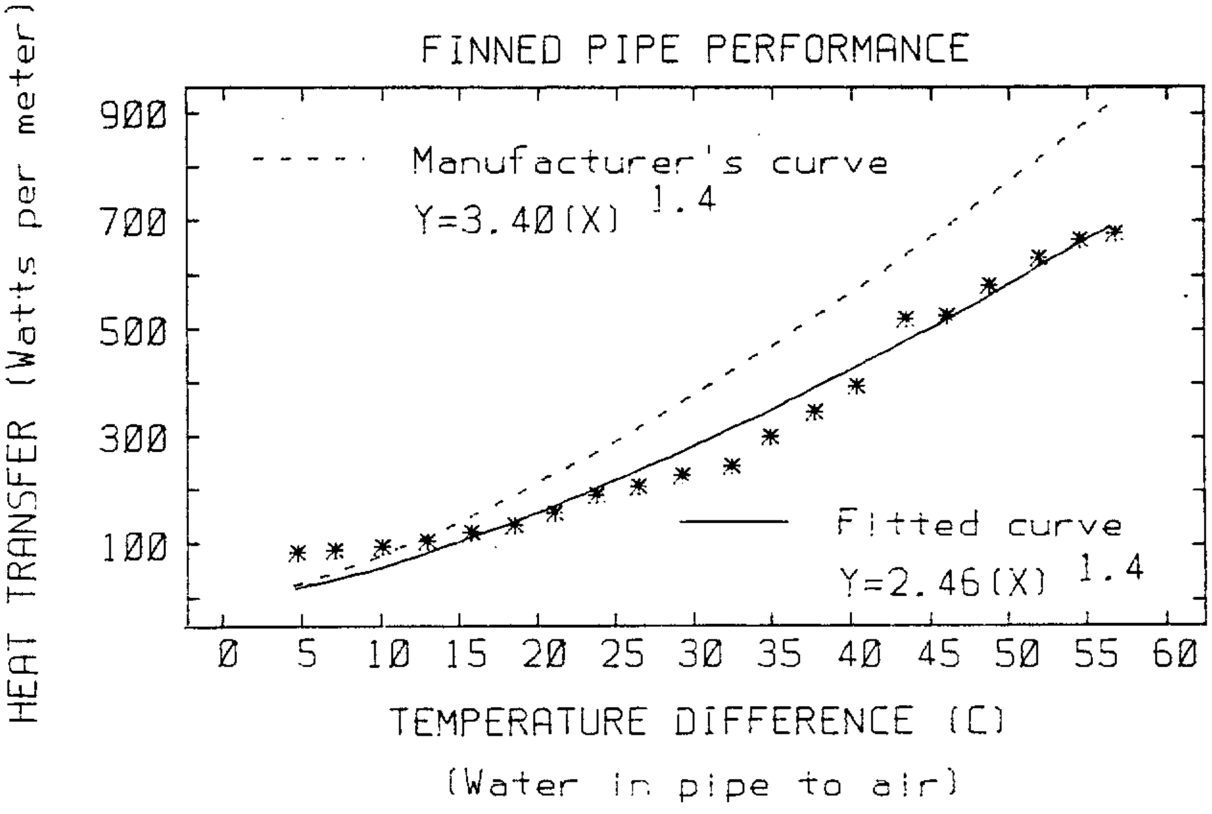

FINNED PIPE PERFORMANCE
Manufacturer's curve
Y=3.40(X) 1.4
Fitted curve
Y=2.46(X) 1.4
HEAT TRANSFER (Watts per meter)
900
700
500
300
100
0
5
10
15
20
25
30
35
40
45
50
55
60
TEMPERATURE DIFFERENCE (C)
(Water in pipe to air)

Fig. 6

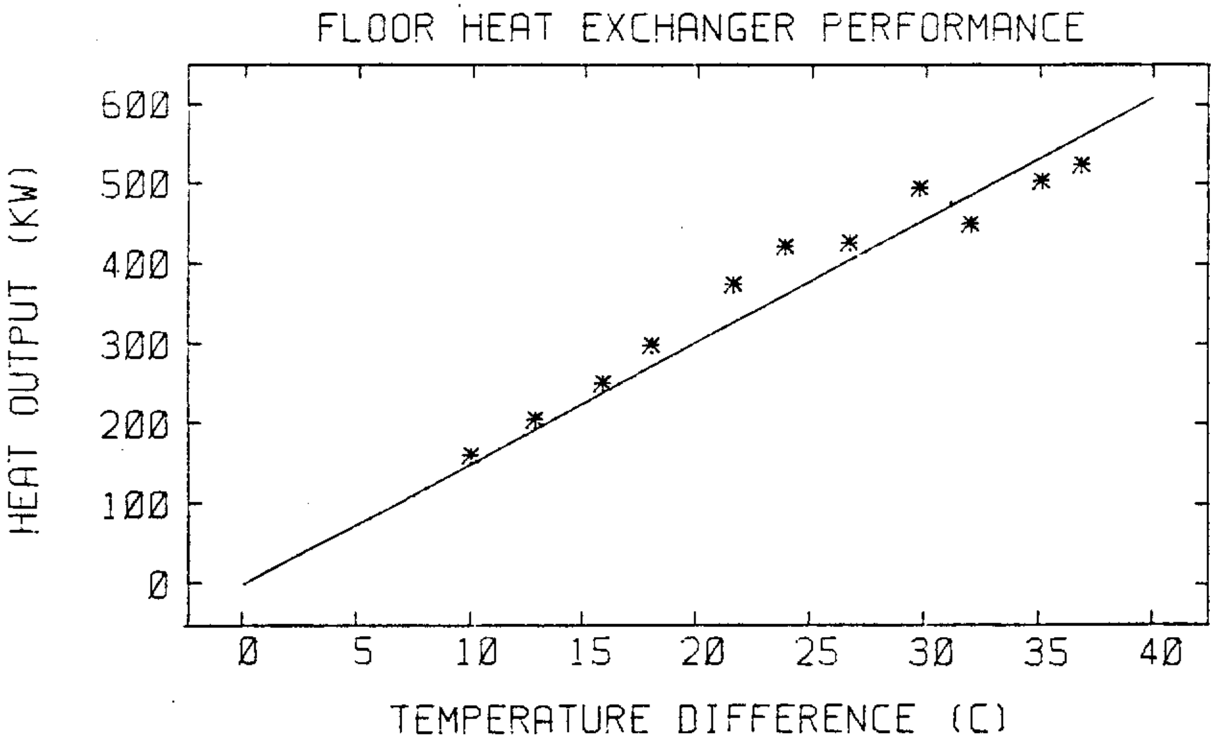

FLOOR HEAT EXCHANGER PERFORMANCE
HEAT OUTPUT (KW)
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
TEMPERATURE DIFFERENCE (C)

Fig. 7

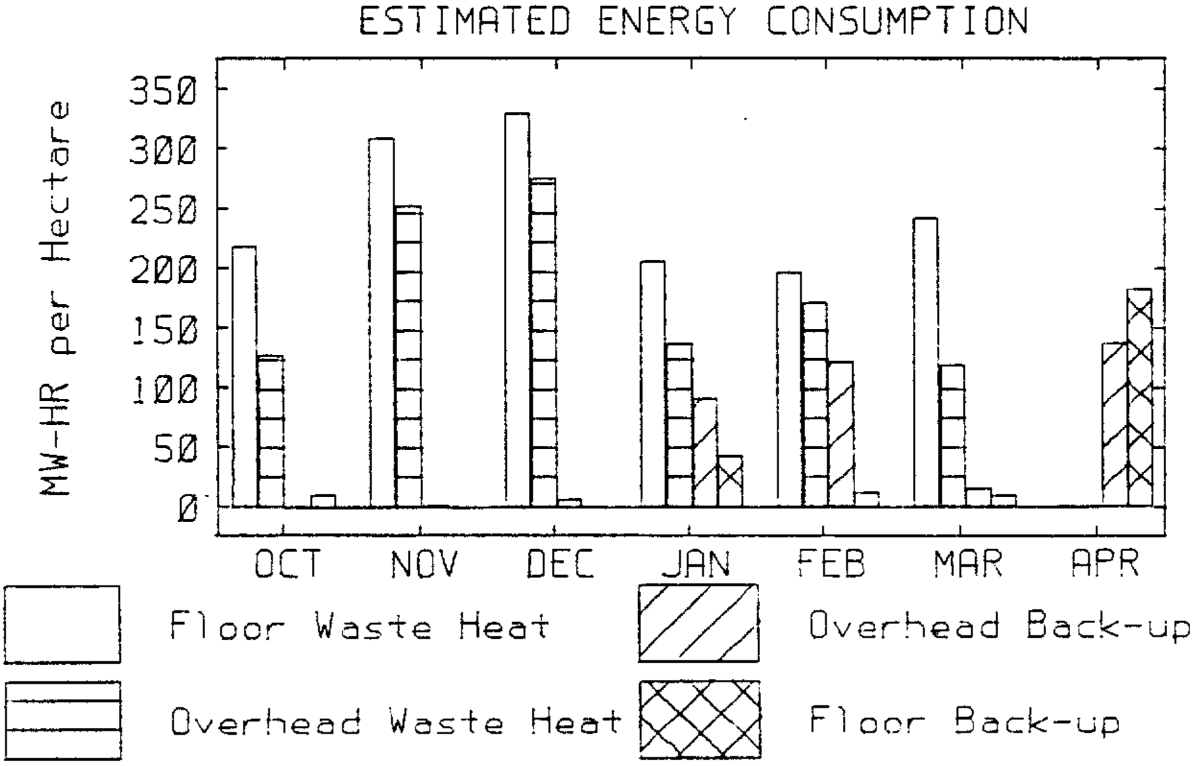

ESTIMATED ENERGY CONSUMPTION
MW-HR per Hectare
350
300
250
200
150
100
50
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
Floor Waste Heat
Overhead Back-up
Overhead Waste Heat
Floor Back-up

Fig. 8