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COMPUTER AIDED DESIGN OF A GREENHOUSE WASTE HEAT UTILIZATION SYSTEM

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SUMMARY:

A 1.1 hectare greenhouse was designed to use warm water discharges from a power plant as the primary heat source. A computer simulation program was used to evaluate several heating system options and predict thermal performance.

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COMPUTER AIDED DESIGN OF A GREENHOUSE WASTE HEAT UTILIZATION SYSTEM

Thomas O. Manning and David R. Mears*

INTRODUCTION

Rapidly escalating fuel costs and increasing uncertainty regarding supply have been very serious concerns for the greenhouse industry in recent years. Most established growers have turned to energy conservation and in some cases changes in cultural practices to alleviate the situation. There has been a substantial research effort on solar energy applications for commercial greenhouses supported by the USDA in recent years. The proceedings of the latest conference held specifically on solar heating of commercial greenhouses and greenhouse residence combinations includes reports on 11 research projects and 5 commercial demonstration projects (Mears, 1979). There have also been a number of studies including several research and development projects on the use of waste heat from electric power generating stations to heat commercial greenhouses. The state of the art was thoroughly reviewed at a conference on waste heat utilization for agriculture and aquaculture in 1978 and in TVA Bulletin Y-132 prepared for that conference.

The objective of the work reported in this paper was to design a prototype greenhouse heating system utilizing warm water from a specific electric power generating station. Realistic information on variations in water supply temperatures and outside ambient conditions were important inputs. To take into account the effects of changes in factors affecting greenhouse energy requirements, computer simulation was extensively used to evaluate a number of possible designs. Site-specific information was available on the weather and the temperature of the power plant's condenser discharge water at hourly intervals over the entire year. Data from research on solar heating of greenhouses was found to be particularly useful, since these solar systems are based on relatively low temperature energy sources so the problems associated with heat transfer from the solar storage system to the greenhouse are very similar to those encountered in designing a system utilizing waste heat.

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DESCRIPTION OF COMPUTER PROGRAM

The design requirement was for a greenhouse utilizing reject heat from a coal fired electric generating station operated by the Pennsylvania Power and Light Company in Montour County, Pennsylvania. Two guidelines helped define the design criteria for the greenhouse. Since warm water might not be available from the power plant for prolonged periods of time, a fossil-fuel backup system was incorporated with the capability of meeting the maximum heating demand of the greenhouse (based on maintaining a 45 °C difference between the greenhouse and outside ambient temperatures). Furthermore, since a back-up heating system is required, the heat exchangers for extracting heat from the power plant water were designed to provide most of the year-round heating needs of the greenhouse and the back-up system will provide any additional heat when the waste heat distribution system is not capable of meeting the load.

In light of these guidelines, computer simulation can provide assistance in selecting the heat exchanger capacity required and in evaluating the relative merits of different means of extracting heat from the warm water. Furthermore, a simulation can be used to investigate the tradeoffs between insulating the greenhouse (reducing heat demand) or increasing heat exchanger capacity, and to determine the effects of different control strategies.

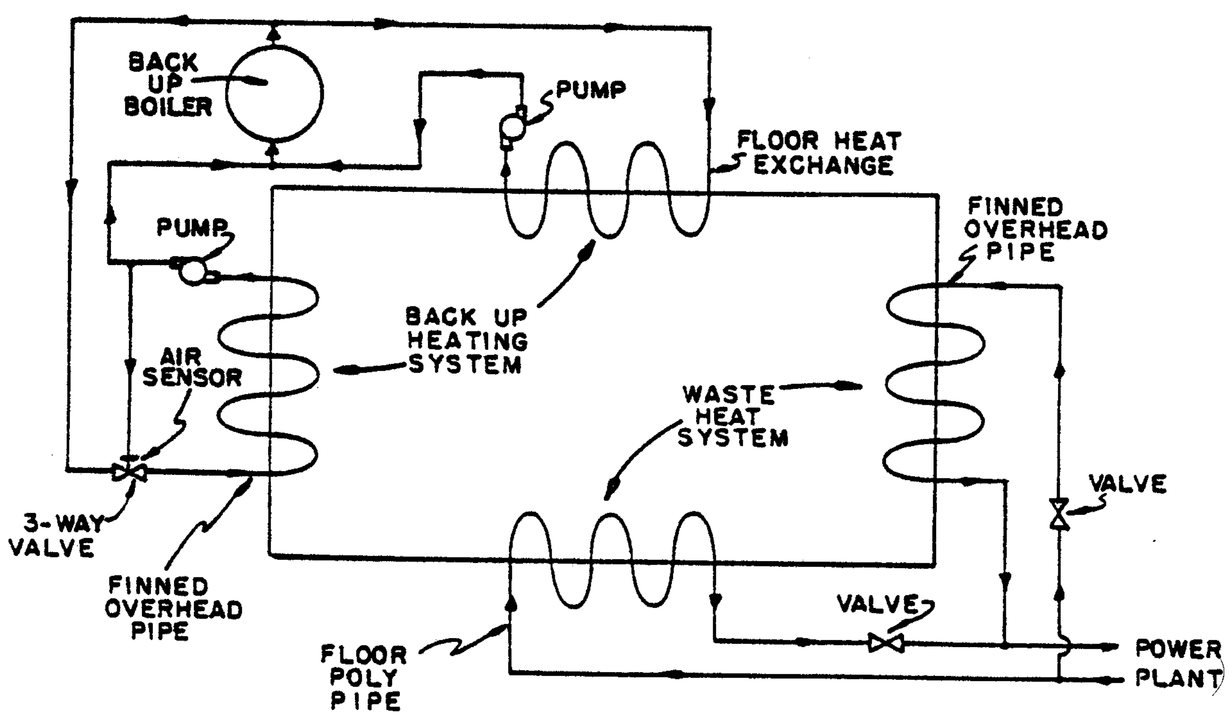


FIG I SCHEMATIC LAYOUT OF WASTE HEAT AND BACK UP HEATING SYSTEMS

The computer simulation program uses power plant discharge and outside ambient temperatures to calculate the expected greenhouse loads and the percentages of the heating requirements that can be carried by the different heating systems. For design of the Montour greenhouse four different heating systems were considered:

- A primary waste heat system consisting of a heated floor.
- A secondary waste heat system consisting of power plant water circulating through finned or other heating pipes, or forced convection units
- A back-up air heating system
- A back-up floor heating system

These systems are shown schematically in Figure I.

Since the objective of the computer program was to compare different heating options, the simulation is reasonably straightforward. The program calculates the hourly heating load, determines the amount of heat available from the primary and secondary waste heat systems, and, if necessary, calculates the additional back-up heat required to match the load. Solar radiation data were not available for the site, and the calculations are not performed for daytime hours. However, daytime supplemental heating requirements in a greenhouse with a warm floor are not expected to be a significant portion of annual heating needs.

The hourly data inputs to the computer program are readings of the water discharge temperatures from the two power plant units and the outside ambient temperature during the period from 5:00 PM to 7:00 AM. The parameters that can be specified by the user are shown in Table I. The program supplies the following outputs:

- Total heating requirements for the greenhouse
- Total energy provided by waste heat
- Total energy provided by back-up heating systems
- Amount of heat provided by primary waste heat system (warm floor)
- Amount of heat provided by secondary waste heat system (overhead pipe)
- Amount of energy required by floor back-up heating system
- Amount of energy required by air back-up heating system (overhead pipe)

If the specified back-up heating system is incapable of providing sufffficient heat to maintain the desired greenhouse temperatures, a printed message indicates this situation and shows what the greenhouse ambient temperature will be for the heat supply to match or exceed the demand. A simplified flow chart of the computer program is shown in Figure II.

TABLE I. LIST OF PARAMETERS AND TYPICAL VALUES

Thermal characteristics:

Heat transfer coefficient of warm concrete floor	5.1	W/m^2K
Heat transfer coefficient of greenhouse roof	3.1	W/m^2K
Heat transfer coefficient greenhouse walls	1.1	W/m^2K
Thermal mass of floor	7050	J/m^2K
Steam rating of finned pipe	6×10^6	J/m
Inside diameter of finned pipe	30	mm
Design water velocity in pipes	0.6	m/sec
Water temperature loss between power plant and greenhouse	2	°C
Number of power plant unit to supply water	2	

Physical characteristics:

Length of greenhouse	64	m
Width of a bay	8.5	m
Height to gutter	3.7	m
Number of bays	20	
Finned pipes for waste heat per bay	2	
Finned pipes for waste heat at ends of bay	1	
Extra finned pipe for waste heat on side walls	0	
Back-up heating pipes per bay	1	
Back-up heating pipes at ends of bay	1	
Extra back-up heating pipes on side walls	0	

Temperature control parameters (°C):

Primary heating thermostat setting	18
Backup heating thermostat setting	17
Flooded floor minimum water temperature	24
Average temperature in backup heating pipes	75
Thermostat setting for heater in dry floor	32

Options:

- Finned or plain pipes for boiler water.
- Ability to circulate back-up boiler water through waste heat distribution system.

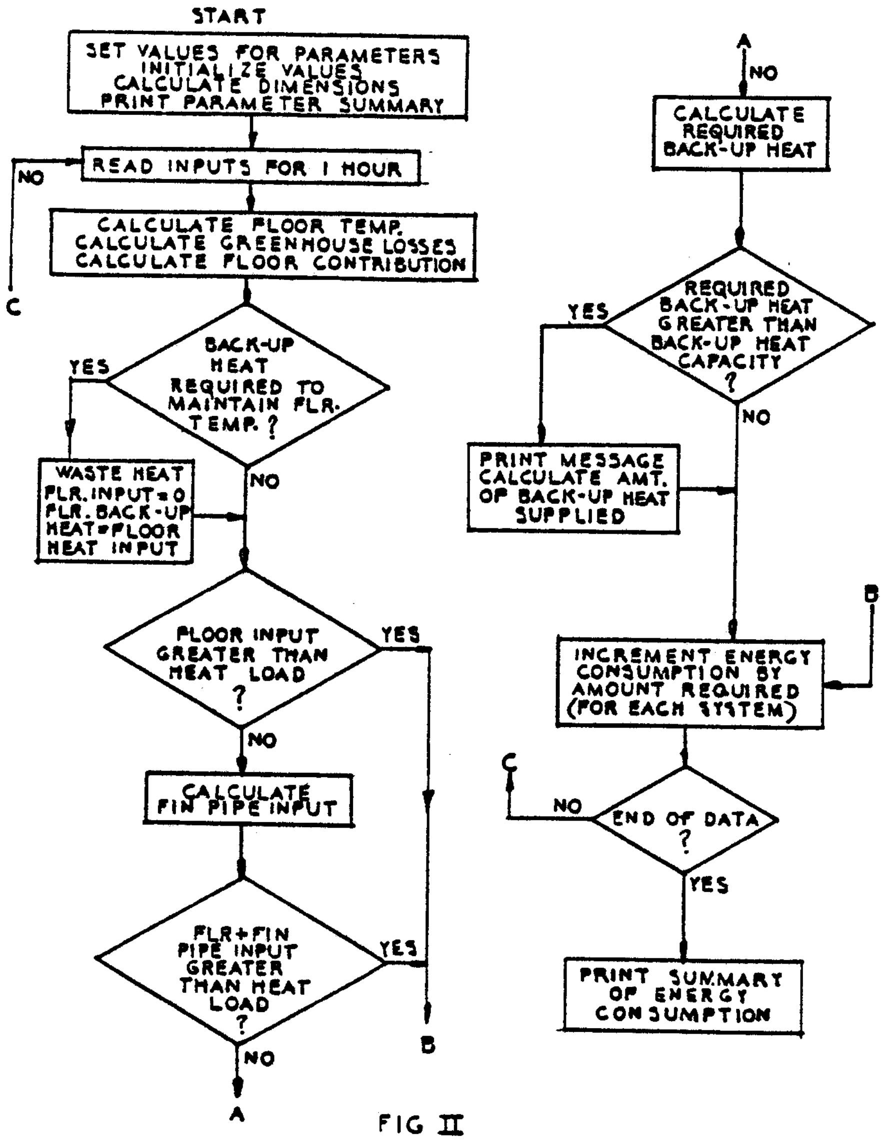


FIG II

DESIGN INFORMATION

The grower, Bryfogle's Inc., specified that the greenhouse heating system should be capable of maintaining 21 °C under all outside weather conditions. For some crops the greenhouse could be held at 18 or 16 °C and the economic impact of operating at either of the lower temperatures should be evaluated. Having specified the desired greenhouse operating temperatures it was then necessary to have data on the outside ambient temperature and the temperature of the available water. In preparing designs of greenhouses to be heated with reject heat, assumptions are frequently made regarding the limiting outside design temperature and the temperature of the waste heat source. However, it must be noted that for any given situation these temperatures will both vary significantly with time. For the Montour power plant, discharge water temperatures were found to vary substantially throughout the heating season.

The Montour power plant is a closed cycle generating station that has been in operation for a number of years and actual data regarding its operation are available. The utility provided a log covering the actual operation of the plant for the entire winter of 1979–'80. The power plant has two identical operating units. In each unit condenser cooling water flows in series through two heat exchangers to a natural draft cooling tower. The logs contain hourly data which include the outside ambient air temperature and the temperatures of the waters leaving each of the four condensers. The warmest water in each unit is that leaving the second condenser. A sample of the data for the month of February, 1979 is shown in Figure III.

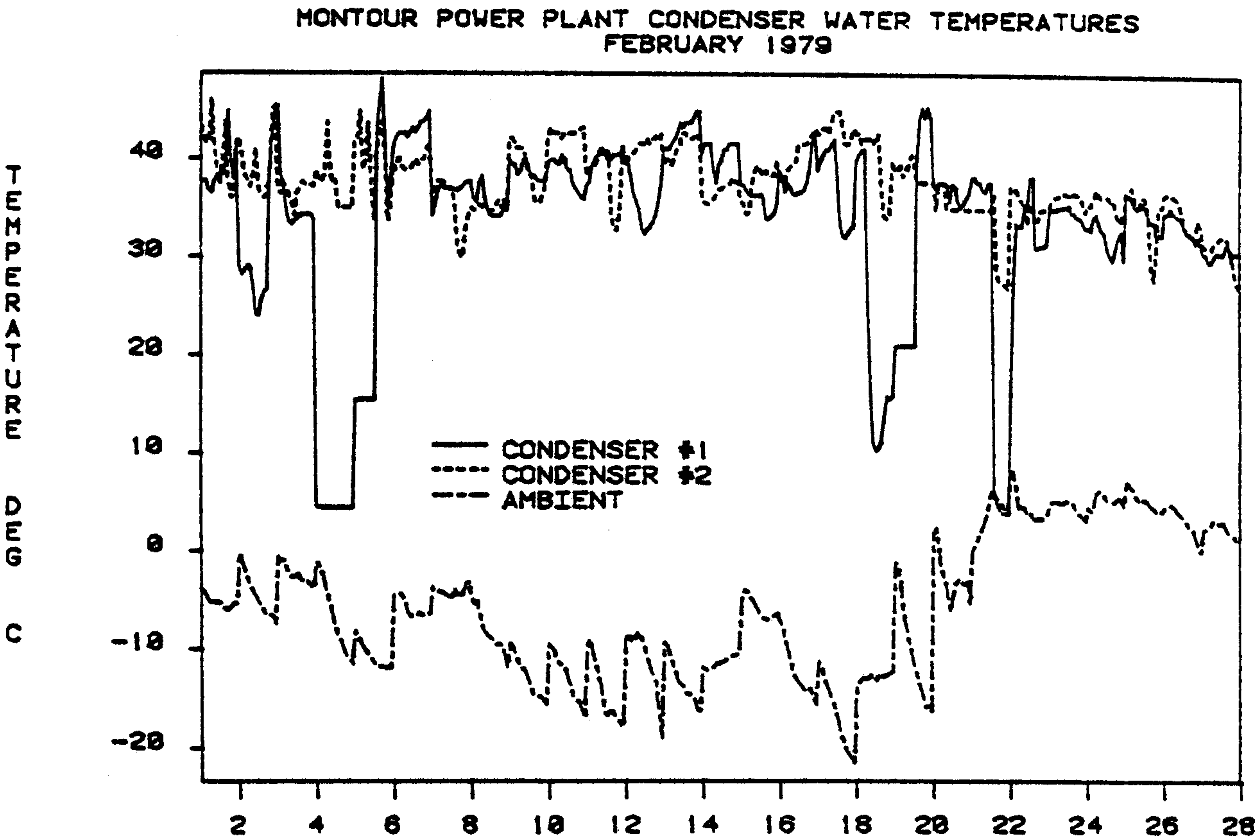


FIGURE III

To calculate the heat load it is necessary to know the dimensions and the heat transfer coefficient of the greenhouse to be constructed. The grower specified the dimensions of the structure and that the greenhouse would be gutter-connected and glazed with a double layer of polyethylene. The option of using a movable curtain insulation system was to be considered in the design process. In order to determine the appropriate heat transfer coefficients, data obtained from a 0.54 hectare demonstration of a solar heating system were utilized (Cipolletti et al, 1980, Mears et al, 1980).

A number of options were considered for transfering heat from the power plant water to the greenhouse. Manufacturers' data were used to determine appropriate heat transfer coefficients for forced convection water/air heat exchangers and finned pipe. ASHRAE standards were used for the heat transfer coefficients for plain pipe. Also, several floor heating systems developed at Rutgers over the past several years were considered for the primary heat exchange mode. Heat transfer coefficients for the various floor systems were taken from several reports on the operation of solar systems, (Mears et al, 1977 and Cipolletti et al, 1980) and from a report on floor heating systems, (Roberts and Mears, 1980). For floor heating systems in which a flooded floor is used, the thermal mass of the floor must be considered in the simulation model and that data is also available in the solar reports cited. The values used for the thermal characteristics of different heating and insulating systems, and the values of temperature settings used in evaluating different control strategies are shown in Table II. Table I includes typical values for other parameters used by the computer program.

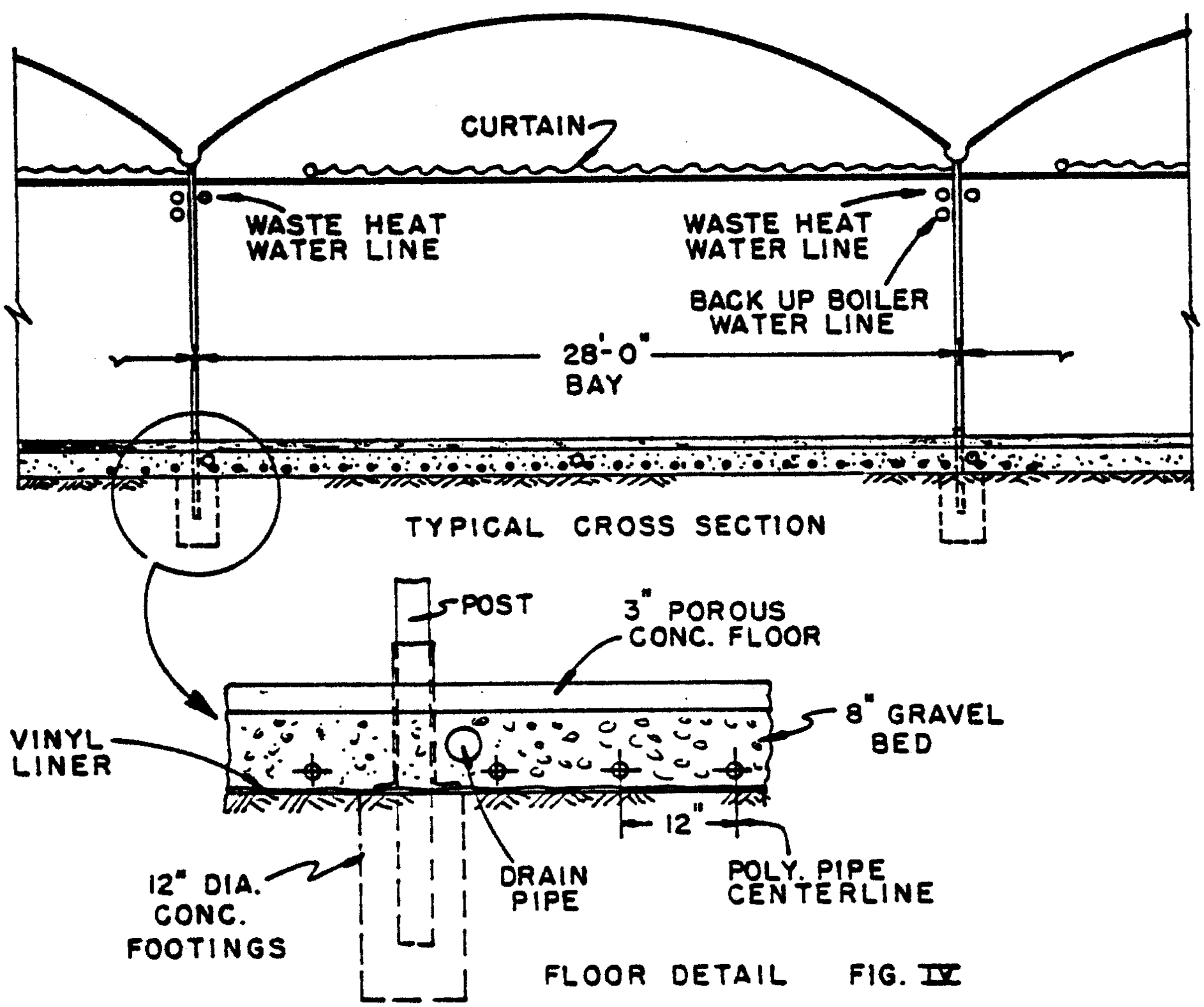
TABLE II. VALUES FOR PARAMETERS USED IN COMPUTER SIMULATION

Floor heat transfer coefficients (W/m^2K):			
Water in flooded floor to greenhouse ambient -	6.8*		
Water in polyethylene pipes in flooded floor to greenhouse ambient - pipes spaced 30 cm. apart -	5.1		
Water in polyethylene pipes in flooded floor to greenhouse ambient - pipes spaced 60 cm. apart -	4.3*		
Water in poly pipes embedded in porous concrete to greenhouse ambient - pipes spaced 30 cm. apart -	3.4		
Greenhouse roof heat transfer coefficients (W/m^2K):			
Greenhouse to outside ambient - Air-inflated double polyethylene cover -	4.5		
Greenhouse to outside ambient - double polyethylene with insulating blanket of summer shade material -	3.1		
Greenhouse to outside ambient - double polyethylene with well-sealed aluminized insulating blanket -	2.3		
Temperature settings (°C):			
Nighttime thermostat settings for air temperature:			
Primary heating system:	21	18	15.5
Back-up heating system:	20	17	15
Themostat settings for adding back-up heat to the floor:	24	30*	

* Simulations were run with these data but the results are not included in this paper.

The designs considered for the greenhouse reflect not only the grower's requirements but also the necessity of providing some redundancy in the heating systems in view of the fact that the operating performance of the components might be affected to an unpredictable degree by factors such as water quality or types of crops grown. The designs were also influenced by the greenhouse geometry chosen by the grower and his preferences in components.

A warm floor of the type shown in Figure IV was considered for the primary waste-heat system. The floor is constructed of a biocide-treated vinyl liner filled with approximately 20 cm of washed coarse gravel that is flooded with water and capped with an 8 cm layer of porous concrete. Power plant water can be introduced directly into the gravel. In order to prevent the possibility of any contaminants from the greenhouse entering into the power plant cycle, the utility specified that the water from the power plant must be kept separate from the water in the gravel by circulating it through polyethylene pipes buried in the gravel. Two alternate designs for such a flooded floor used polyethylene pipes spaced 30 and 60 cm apart. The heat transfer rates from the power plant water to the greenhouse air, based on the surface area of the porous concrete, are shown in Table II. Note that the option of introducing water directly into the flooded floor has a significantly higher heat transfer coefficient than any of the systems in which power plant water is contained in pipes.



FLOOR DETAIL FIG. IV

An alternate possibility for the floor heat exchanger is a dry porous concrete floor, which consists of polyethylene pipe spaced 30 cm apart embedded directly in a 8 cm layer of porous concrete floor. Advantages of the flooded floor over the dry floor include higher heat transfer rates and the considerable thermal mass in the water and gravel, which may allow the greenhouse to utilize stored heat during periods when the power plant is not operating. Also, the ability to introduce water directly into the gravel provides an alternate system in the event that the pipes in the floor become restricted for any reason.

Several options were considered for the secondary waste heat distribution system including the use of unit heaters located in the upper part of the greenhouse and spaced to provide uniform heating. An estimate of the numbers and water flows required for the unit heaters discouraged further consideration of this concept. Another option was the use of finned pipe as a conduit for the power plant water. Some simulations were run with two finned pipes located below each gutter, as shown in Figure IV. This configuration was chosen in part due to the relative ease of supporting the pipe directly below the gutters.

The greenhouse design is based on the use of double layer polyethylene glazing, and insulating blankets were considered as options to explore the possibilities of reducing heat exchanger requirements by lowering heating demand and because of the possible use of insulating curtains for shading or day length control. Two insulating blanket systems were considered, one using a somewhat porous thermal barrier, which could be used as a partial summer shade, and the other using a tighter, aluminized curtain material. The heat transfer rates for the greenhouse without curtains and with both types of blanket materials are shown in Table II. These values are based on the temperature difference between the greenhouse growing area and the outside ambient, and the exposed greenhouse surface area.

Parameters that may be specified for the simulation include various controllable temperature settings. The greenhouse ambient temperatures considered were based on the grower's needs, and are shown in Table II. More heat can be extracted from the power plant water if back-up heat is not added to the floor heating system until the power plant water temperature approaches the greenhouse ambient temperature. However, in order to maintain uniform, elevated soil temperatures, the floor water temperature should be somewhat warmer than the greenhouse ambient. Most simulations were run with the back-up heat for the floor set to come on when the floor water temperature reached 24 °C. In dry floor systems, the temperature of the boiler water that circulates through the pipes in the concrete can be set. Most simulations were run with this parameter set to 32 °C, since raising the temperature will increase the fossil-fuel requirements, and a lower temperature will not provide the required soil heating. Information on temperature settings is included in Table II.

RESULTS

The simulations for which information has been presented were run for conditions closely resembling those that were expected for the Montour greenhouse site. The values for the parameters in Table I that concern the physical and the thermal characteristics correspond to the specifications for the 1.1 hectare greenhouse actually constructed. The pipeline that has been constructed at the greenhouse site is connected to cooling tower #2, which is usually shut down in the spring for annual maintenance. The computer simulations are based on using the water from unit #2 , which, during the 1979-'80 heating season, was not operating for most of the month of March.

Some projections for greenhouse energy requirements per hectare of greenhouse based on data for the 1979-'80 heating season are shown in Tables III and IV. Some of these data are displayed graphically in Figures V, VI and VII. In these graphs, data are presented for designs in which waste heat is introduced into a flooded floor through polyethylene pipes spaced 30 cm apart, and pipes in a dry floor are also assumed to be on a 30 cm spacing. Projections based on the use of finned pipes as secondary heat exchangers assume that two rows of pipe will be installed in each bay. A number of computer runs were made with other combinations of the parameters in Table I. These representative results include the final design selected and illustrate the effects of changes in system design.

Figure V illustrates how the total heating requirements in a greenhouse with a flooded floor are affected by insulation, and how the percentage of the total heat requirement provided by waste heat is influenced by insulation and the use of finned pipes as a secondary heat exchanger. The portion of the heat demand provided by the back-up heating system is shown in more detail in Figure V. These graphs demonstrate some of the limitations that determine the maximum energy savings that can be achieved. Back-up heating costs should be relatively insignificant for a greenhouse that is insulated, which has finned pipes as secondary heat exchangers for the waste heat, or which is operated at a low or intermediate temperature. As indicated in Figure VI, the back-up heating requirements can only be reduced to a certain point. This reflects the fact that the back-up heating requirements represent heat demand primarily when warm water is not available from the power plant due to a shutdown. Furthermore, the quantity of heat provided by a warm floor is determined by the temperature of the water and the greenhouse thermostat setting and is independent of the outside temperature. The quantity of back-up heat required by the warm floor does not depend on greenhouse insulation or secondary heat exchanger capacity. Consequently, when supplemental heating requirements are reduced to the point where the majority of the heat can be provided by a warm floor, increasing insulation or heat exchanger capacity will not result in any significant further reductions in back-up heat requirements.

Figure VII provides a comparison between the use of a flooded floor with the warm water in pipes on 30 cm spacing and a dry floor as the primary heat exchanger for waste heat for several different greenhouse conditions. This graph also illustrates the degree to which the greenhouse ambient temperature affects the supplemental heat requirement, and shows some of the interactions between the temperature setting and heating system design. Note that the better heat transfer obtainable in the flooded floor dramatically reduces the need for insulation and finned pipe.

A number of computer runs were made to determine the usefulness of the thermal mass of the flooded floor and to determine effective strategies for controlling water flow. It was found that if the greenhouse could be connected to both power plant cooling towers warm water should be provided from whichever unit was operating at the highest temperature. There were periods when the temperature of the available water was falling, and under these conditions it would be desirable to shut off the flow through the floor whenever the temperature of the water from the power plant was reduced to the point where no heat could be added to the floor system. In this condition it is better to coast on stored energy than to continuously circulate power plant water. One very interesting possibility suggested by examination of the interactions of the control strategy and the various systems simulated is that of a substantial potential benefit in developing a computer based control system for such a facility.

CONCLUSIONS

The predictions of annual supplemental heating requirements indicate that certain design options may be interchangeable. In particular, the installation of insulating curtains or two rows of finned pipe in each bay will reduce back-up heat requirements to approximately the same level in a greenhouse with a flooded floor. Alternatively, the heating requirements are roughly the same for a greenhouse with a dry floor and two rows of finned pipe overhead per bay or for a greenhouse with a flooded floor and no overhead finned pipe. The actual greenhouse design consists of a flooded floor, a blanket insulating system, and two rows of finned pipe in each bay, as shown in Figure IV. The material selected for the thermal curtain is an open weave cloth which has been shown to reduce the heat tranfer rate for a double glazed polyethylene covered greenhouse to 3.1 W/m^2K (Cipolletti et al, 1980). Detailed layouts of the systems actually installed are illustrated in Figures VIII - XI. This design is conservative and from the perspective of thermal performance the greenhouse is considerably overdesigned . As previously mentioned, however, some of the redundancy of the design is intended to ensure the operation of the greenhouse even if the performance of some of the components degrades with time as a result of fouling, corrosion, or other factors.

Selection of a suitable design for the greenhouse was influenced by a number of factors besides the thermal performance of the systems evaluated and the need for a certain amount of redundancy. The first important decision was the selection of a flooded floor as the primary heat exchanger, with the waste heat introduced through a network of polyethylene pipes embedded in the gravel which are spaced 30 cm apart. Some of the factors which influenced this choice include the high thermal inertia of this floor system, the constraint that power plant water be kept in a closed loop isolated from the greenhouse environment, and the higher heat transfer rates and more uniform distribution of heat from a flooded floor.

Having determined the form that the floor system would take, the next step was to determine whether to install insulating curtains or additional heat exchange surface (finned pipes). Although either one of these two would suffice to reduce back-up heating requirements to 10% or less of those for a similar conventionally heated double-glazed greenhouse, the final design specified both insulating curtains and finned pipes for a number of reasons. Advantages of insulating blankets include the fact that the curtain can be used for shading or daylength control. The material selected by the grower is a partial shade cloth which can be used to reduce ventilation loads and light levels in the summer months. An advantage of the finned pipes is that they will provide heat in the daytime in conditions when the floor does not provide adequate energy and a curtain system would not be closed.

The costs of installing pipelines are an incentive for minimizing the quantities of water required per hectare of greenhouse. Evaluating the tradeoffs between insulating blankets and finned pipes should therefore consider the water requirements for alternate designs. The decision to install a curtain and finned pipes not only helps ensure that the system will perform satisfactorily, but also offers an opportunity to weigh the advantages and disadvantages of each in the field.

The main use of the computer simulation program in designing the waste heat greenhouse in Montour was as a means of comparing different design options and exploring the interactions between heating systems, power plant water and outside ambient temperatures, and temperature control strategies. The program was particularly valuable because it helped identify innovative possibilities for heating system configurations and control strategies for a greenhouse using power plant discharges as the primary heat source. The actual design reflects the need for a laboratory where some of these possibilities can be explored under actual operating conditions.

An important next step is the detailed monitoring of greenhouse performance and experimentation with different temperature regimes in order to determine what improvements and modifications can be made in future designs, with a particular view toward determining what the minimal requirements might be for specific applications and how the pipeline capacity can be most effectively utilized. A data acquisition system will be installed to gather detailed information on the greenhouse performance during the 1981-'82 heating season. By measuring the actual contributions of each element in the system to the greenhouse energy budget it will be possible to refine the model used in this study and improve the efficiency of future designs. After the actual costs of the separate elements of the system are determined economic judgements can be made regarding the value of the contribution to the heating demand.

ACKNOWLEDGEMENTS

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TABLE III. PROJECTED YEARLY PERFORMANCE PER HECTARE: FLOODED FLOOR ($U = 5.1\ W/m^2K$)

BACK-UP HEAT THERMOSTAT IN FLOODED FLOOR SET TO 24 °C

Two overhead finned pipes in each bay for waste heat:

THERMOSTAT SETTING	U GREENHOUSE	FLOOR BACK-UP	OVERHEAD BACK-UP	FLOOR WASTE HEAT	OVERHEAD WASTE HEAT	BACK-UP TOTAL	WASTE-HEAT TOTAL	WASTE-HEAT PERCENTAGE	TOTAL ENERGY
°C	W/m^2K	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	%	$J\ x10^{12}$
21	4.5	0.08	1.31	4.66	3.81	1.39	8.47	86	9.86
18	4.5	0.10	0.47	4.93	3.06	0.57	7.99	93	8.56
15.5	4.5	0.13	0.08	4.95	1.90	0.21	6.84	97	7.06
21	3.1	0.08	0.31	4.30	2.40	0.39	6.70	95	7.09
18	3.1	0.10	0.08	4.50	1.40	0.18	5.89	97	6.07
15.5	3.1	0.12	0.01	4.27	0.56	0.13	4.83	97	4.96
21	2.3	0.06	0.10	4.33	1.20	0.16	5.17	97	5.32
18	2.3	0.08	0.02	3.94	0.48	0.10	4.42	98	4.52

No overhead finned pipes for waste heat:

THERMOSTAT SETTING	U GREENHOUSE	FLOOR BACK-UP	OVERHEAD BACK-UP	BACK-UP TOTAL	WASTE-HEAT TOTAL	WASTE-HEAT PERCENTAGE	TOTAL ENERGY
°C	W/m^2K	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	%	$J\ x10^{12}$
21	4.5	0.07	2.68	2.74	6.94	72	9.68
18	4.5	0.10	1.33	1.43	6.99	83	8.42
15.5	4.5	0.14	0.38	0.52	6.44	92	6.96
21	3.1	0.07	0.78	0.85	6.12	88	6.96
18	3.1	0.10	0.24	0.34	5.68	94	6.02
15.5	3.1	0.14	0.02	0.16	4.79	97	4.95
21	2.3	0.07	0.20	0.27	5.01	95	5.28
18	2.3	0.10	0.03	0.13	4.38	97	4.51
15.5	2.3	0.13	0	0.13	3.55	96	3.69

TABLE IV. PROJECTED YEARLY PERFORMANCE PER HECTARE: PIPE IN DRY POROUS CONCRETE ($U = 3.4\ Wm^2K$)

BACK-UP HEATING SYSTEM FOR FLOOR COMES ON WHEN WATER TEMPERATURE GOES BELOW 24 °C
TEMPERATURE OF FLOOR BACK-UP WATER SETTING IS 32 °C

Two overhead finned pipes in each bay for waste heat:

THERMOSTAT SETTING	U GREENHOUSE	FLOOR BACK-UP	OVERHEAD BACK-UP	FLOOR WASTE HEAT	OVERHEAD WASTE HEAT	BACK-UP TOTAL	WASTE-HEAT TOTAL	WASTE-HEAT PERCENTAGE	TOTAL ENERGY
°C	W/m^2K	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	%	$J\ x10^{12}$
21	4.5	0.07	0.67	6.62	2.70	0.73	9.31	93	10.0
18	4.5	0.10	0.20	6.77	1.58	0.31	8.36	97	8.66
15.5	4.5	0.14	0.02	6.32	0.61	0.16	6.93	98	7.09
21	3.1	0.07	0.16	5.83	1.11	0.23	6.94	97	7.17
18	3.1	0.10	0.03	5.77	0.39	0.13	5.96	98	6.09
15.5	3.1	0.13	0	4.76	0.07	0.13	4.83	97	4.97
21	2.3	0.06	0.05	4.88	0.35	0.12	5.23	98	5.35
18	2.3	0.09	0.01	4.35	0.08	0.10	4.43	98	4.53
15.5	2.3	0.13	0	3.55	0	0.13	3.56	97	3.69

No overhead finned pipes for waste heat:

THERMOSTAT SETTING	U GREENHOUSE	FLOOR BACK-UP	OVERHEAD BACK-UP	BACK-UP TOTAL	WASTE-HEAT TOTAL	WASTE-HEAT PERCENTAGE	TOTAL ENERGY
°C	W/m^2K	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	$J\ x10^{12}$	%	$J\ x10^{12}$
21	3.1	0.08	2.07	2.15	4.61	68	6.75
18	3.1	0.10	1.09	1.19	4.68	80	5.87
15.5	3.1	0.13	0.34	0.47	4.38	90	4.85
21	2.3	0.08	0.79	0.87	4.25	83	5.11
18	2.3	0.10	0.29	0.39	4.05	91	4.44
15.5	2.3	0.12	0.05	0.17	3.50	95	3.67

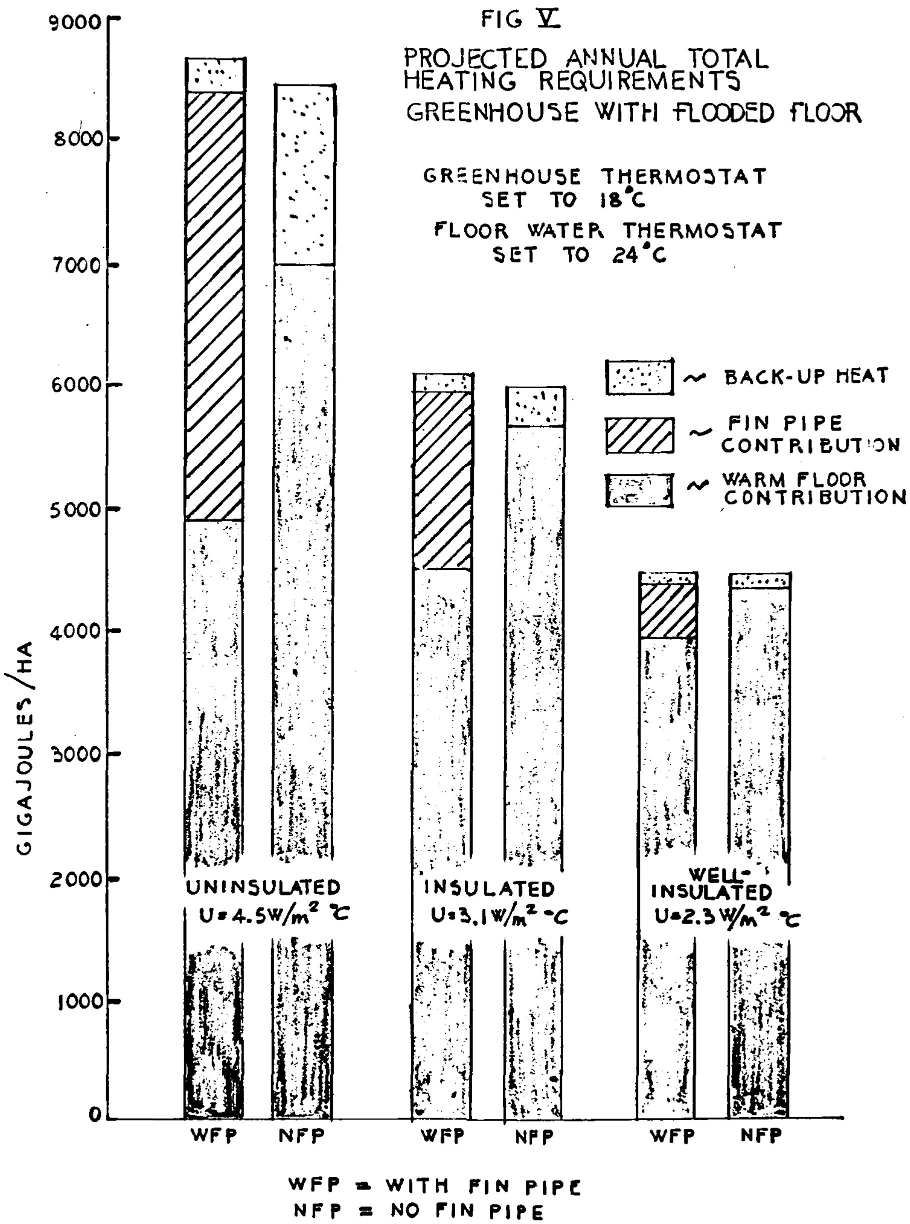


FIG V
PROJECTED ANNUAL TOTAL
HEATING REQUIREMENTS
GREENHOUSE WITH FLOODED FLOOR
GREENHOUSE THERMOSTAT
SET TO 18°C
FLOOR WATER THERMOSTAT
SET TO 24°C
~ BACK-UP HEAT
~ FIN PIPE CONTRIBUTION
~ WARM FLOOR CONTRIBUTION
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
GIGAJOULES/HA
UNINSULATED
U=4.5W/m² °C
INSULATED
U=3.1W/m² °C
WELL-INSULATED
U=2.3W/m² °C
WFP
NFP
WFP
NFP
WFP
NFP
WFP = WITH FIN PIPE
NFP = NO FIN PIPE

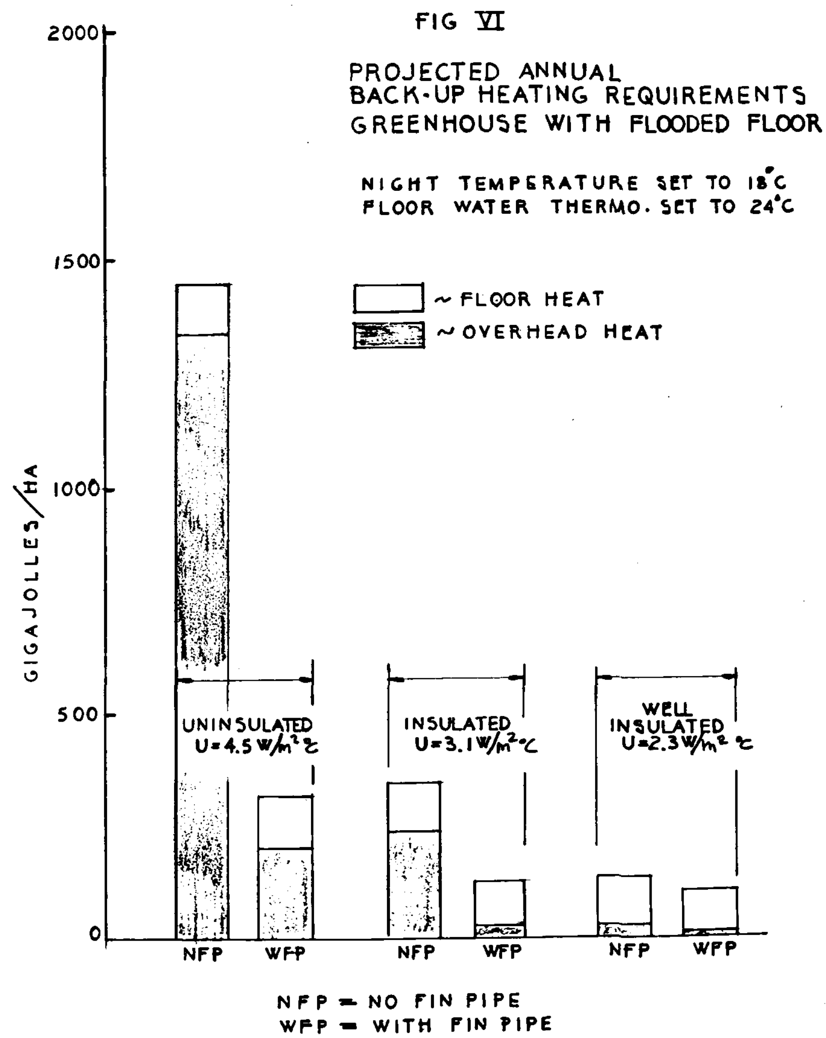


FIG VI
PROJECTED ANNUAL
BACK-UP HEATING REQUIREMENTS
GREENHOUSE WITH FLOODED FLOOR
NIGHT TEMPERATURE SET TO 18°C
FLOOR WATER THERMO. SET TO 24°C
~ FLOOR HEAT
~ OVERHEAD HEAT
2000
1500
1000
500
0
GIGAJOULES/HA
UNINSULATED
U=4.5W/m² °C
INSULATED
U=3.1W/m² °C
WELL INSULATED
U=2.3W/m² °C
NFP
WFP
NFP
WFP
NFP
WFP
NFP = NO FIN PIPE
WFP = WITH FIN PIPE

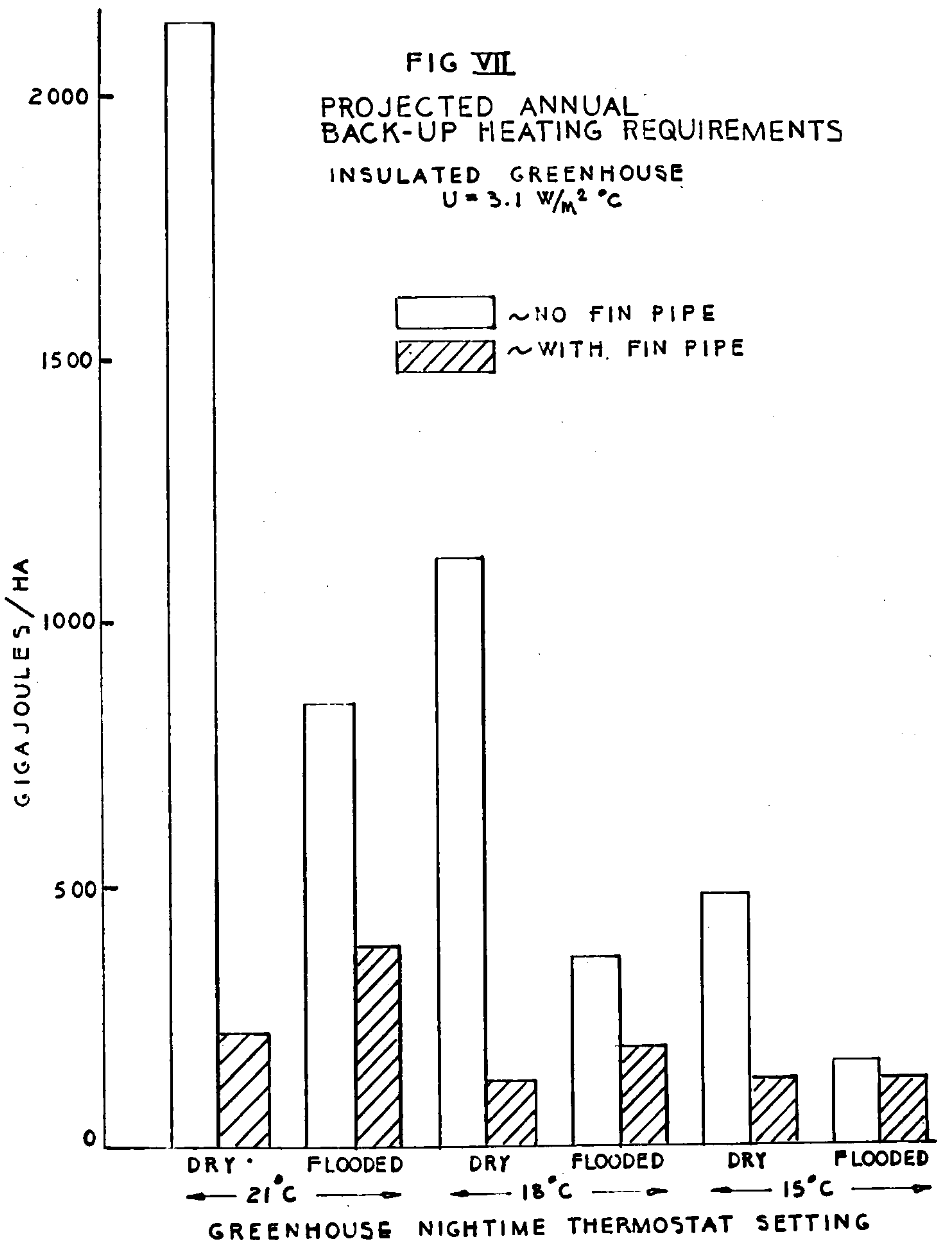
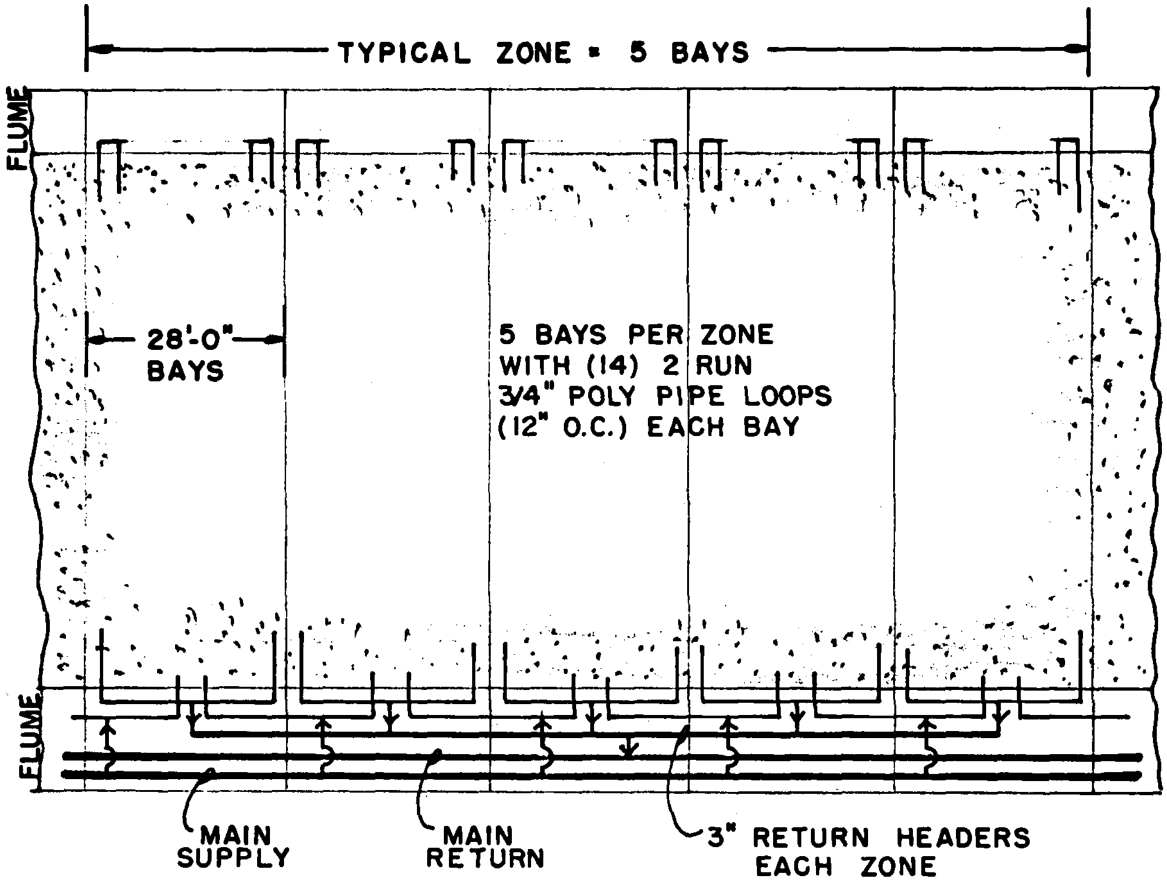
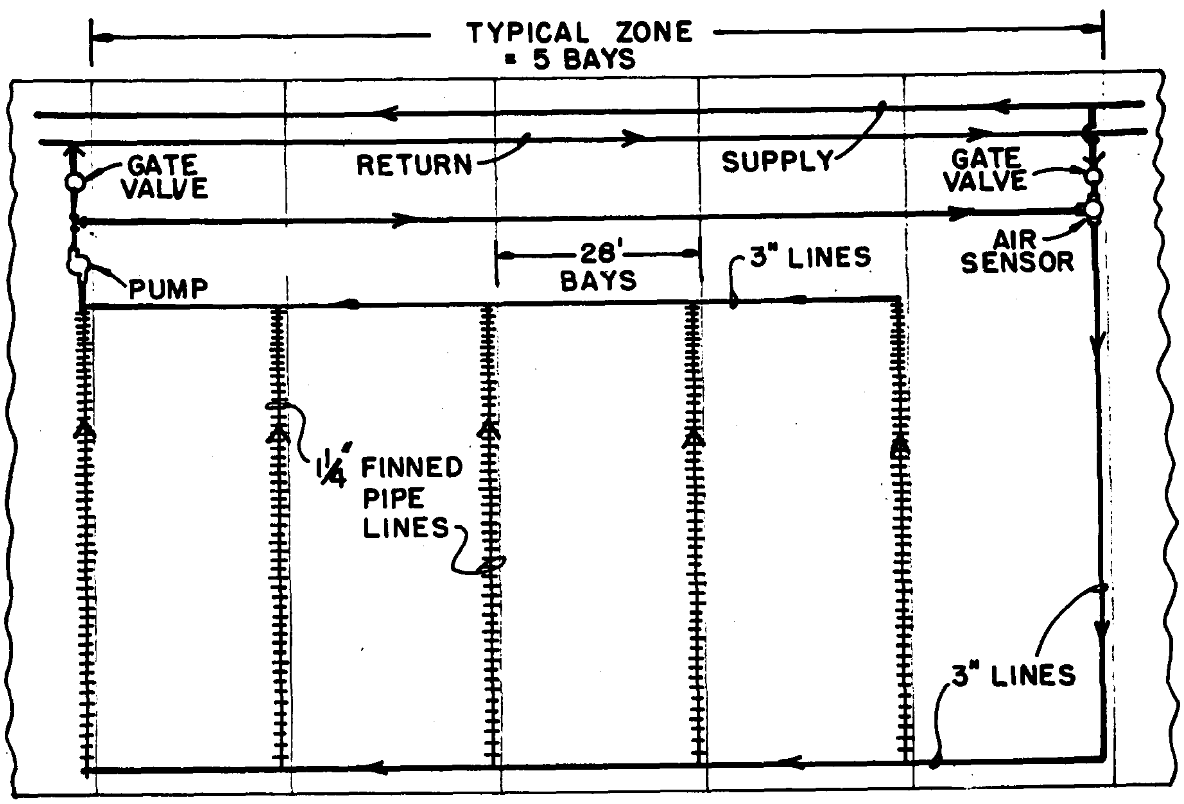


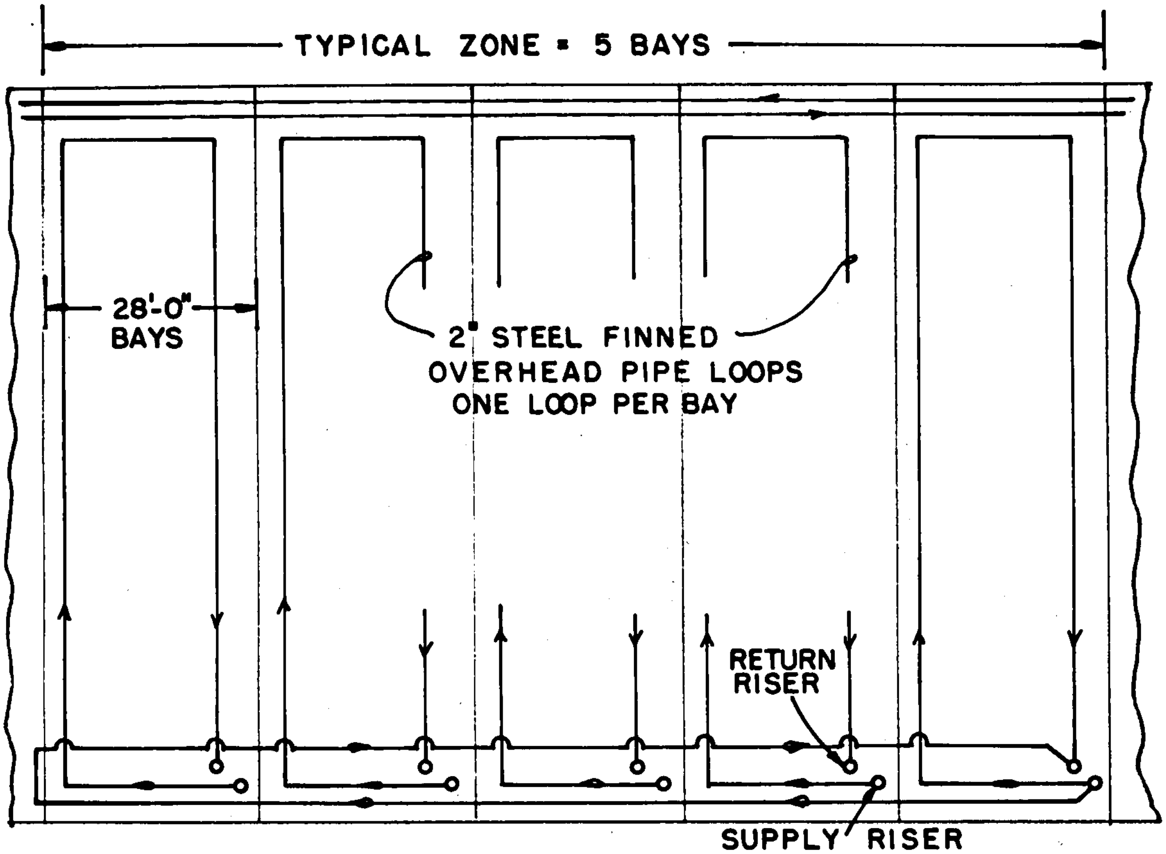
FIG VII
PROJECTED ANNUAL
BACK-UP HEATING REQUIREMENTS
INSULATED GREENHOUSE
U = 3.1 W/m² °C
~NO FIN PIPE
~WITH FIN PIPE
GIGAJOULES/HA
2000
1500
1000
500
0
DRY
FLOODED
DRY
FLOODED
DRY
FLOODED
21°C
18°C
15°C
GREENHOUSE NIGHTIME THERMOSTAT SETTING



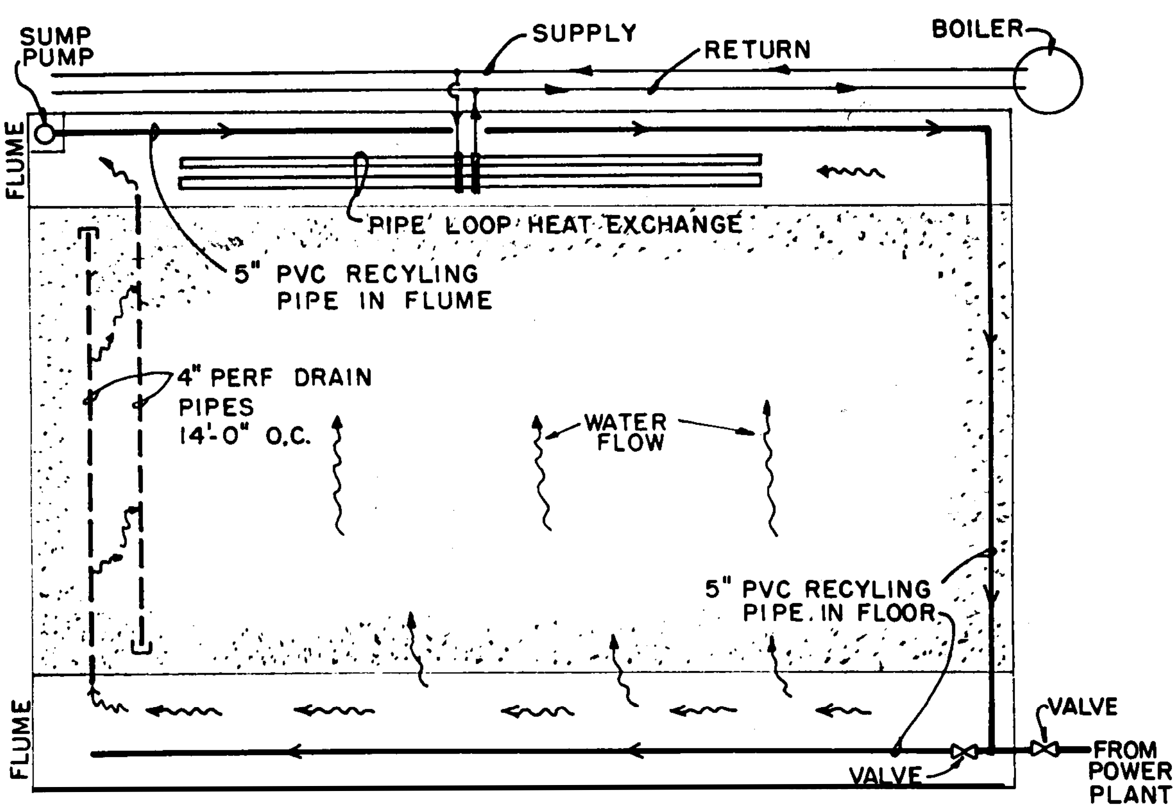
WASTE HEAT FLOOR HEATING SYSTEM



BACK-UP OVERHEAD PIPE HEAT SYSTEM



WASTE HEAT OVERHEAD FINNED PIPE HEAT SYSTEM



BACK-UP FLOOR HEATING SYSTEM