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REDESIGN OF A GREENHOUSE WASTE HEAT SYSTEM

David R. Mears and Thomas O. Manning

Summary: Power Plants, Inc. started in 1980 as a 1.1 hectare greenhouse in Washingtonville, PA using waste heat from Pennsylvania Power and Light's Montour Generating Station. The facility has since expanded to more than 6 hectares. Events in 1993 provided an opportunity to revise the design of the heating system. This paper discusses the design procedure and the subsequent improvements of the system.

KEYWORDS: Greenhouse, design, waste heat

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David R. Mears and Thomas O. Manning, Rutgers University
Kenneth Bryfogle, Power Plants Inc.

INTRODUCTION

Background:

In the late 1970's, at a time when great attention was being placed on the issue of fuel conservation, Pennsylvania Power and Light Company, (PP&L) was looking for a project that would truly conserve energy, create jobs, and show that the utility was forward-looking, creative and conservation minded. In this environment the prospect of developing greenhouses that would use waste heat from the generating station was attractive to PP&L. One cold March morning, standing in the ash basin of the Montour Generating Station, Dr. Heinz Pfeiffer, PP&L Manager of Technology and Energy Assessment, selected Kenneth Bryfogle to be a partner in developing a greenhouse complex that would use the waste heat generated at the Montour Generating Station. Ken Bryfogle's well-established greenhouse operation was an attractive candidate as a first customer for the Montour Agribusiness Center. Together they prepared a proposal for partial support of the project. Later they decided to seek engineering assistance from the greenhouse research faculty at Rutgers University. The research program at Rutgers had developed the technical basis for practical greenhouse heating using waste heat in the temperature range available from the cooling towers at Montour.

The design of the first prototype had a number of conceptual differences from other demonstration projects around the country. First, the project intended to use only cooling water from the power plant, which is truly wasted energy, as it is dumped into the environment with no prospect of use. There was never any consideration of using low quality steam or hot water in a cogeneration mode. Second, the system was designed to use the most energy efficient greenhouse technology available at the time, thereby optimizing the capital investment in heat delivery systems and the pipeline. Most other projects at the time assumed that there was no incentive for conservation, as waste energy or cogenerated energy was "free". Third, the pricing of the energy to the greenhouse complex would be based on maximum water consumption per acre rather than energy consumption, since peak water flow determines the pipeline capacity. This sets an annual per acre price based on the total flow required for an efficient heating system. When it is consistently implemented, this pricing policy provides an incentive for efficient system design.

ORIGINAL DESIGN

The original design objective was to create a prototype greenhouse heating system employing warm water from the Montour generating station. To take into account the effects of changes in factors affecting greenhouse energy requirements, the design process used extensive computer simulation to evaluate a number of possible designs based on heat exchange and energy conservation technology available at the time (Manning and Mears, 1981). PP&L provided site-specific information on the weather and the temperature of the power plant's condenser discharge water at hourly intervals over the entire preceding year.

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The computer simulation was used to optimize the investments in energy conservation systems, floor and overhead heat delivery systems using waste heat from the power plant and the fossil fuel back up system, which was also used for touch-up heat under extreme weather conditions. Using the backup system for touch-up allowed for a much reduced capital investment in heat transfer capacity within the greenhouse and pipeline flow capacity as compared to designing for meeting peak requirements with the relatively low temperature waste heat resource.

Initial System Description:

The original 1.1 hectare greenhouse consists of twenty gutter-connected 64 x 8.5 m bays. The roof glazing is double-layer, air-inflated polyethylene, and the outside walls were originally covered with ultraviolet-resistant, translucent fiberglass panels. Later the walls were changed to double-layer polycarbonate panels. Overhead movable insulating blankets reduce the heat load at night and can provide photoperiod control or daytime shading. A flooded floor system is the primary heat exchanger for the greenhouse. It is constructed of a 0.5 mm biocide-treated vinyl swimming pool liner filled with 20 cm of gravel, which is flooded with water and covered with a 7.5 cm cap of porous concrete. The water and gravel provide thermal storage and are heated by the condenser discharge water which flows through 64 m lengths of 1.9 cm polyethylene pipe embedded in the gravel on 30.5 cm centers. Two 3.2 cm finned pipes underneath each gutter initially served as secondary heat exchangers for the waste heat. The power plant water is supplied to these two systems by a PVC header system starting with a 20 cm diameter, 170 m long main along the east wall of the greenhouse. This header system connects directly to the 50 cm polyethylene main pipes from the utility cooling towers.

The back-up heating system initially consisted of two boilers, one oil-fired and one fired with either oil or coal. Boiler water pumped through a supplementary finned pipe under each gutter provided touch-up air heating when needed. A heat exchanger constructed of 10 loops of galvanized steel pipes each 89.6 m long is located in a water flume along the west wall of the greenhouse and connected to the boiler. This can maintain water temperatures in the floor at desired levels when warm water from the power plant is not available. These back-up heating systems are 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 5.2 kW pump in the southwest corner of the greenhouse circulates water through the gravel in the floor. A system of 10 cm perforated drain pipes in the floor on 4.3 m centers distributes the water flow evenly through the floor when the back-up floor heating system is needed.

The first heating system design called for peak water flow of about 3,700 l/min per hectare. Water circulated in parallel in the floor and in overhead finned pipe. Monitoring energy flows showed that the floor system, using somewhat over half the flow, provided most of the baseload heating requirement over the season. Switching designs in the future to using waste heat only in the floor was an option for extending acreage. Initial estimates were for 8 hectares of greenhouse at this rate without pumping of the 50 cm line, which was designed by engineers at the utility. The first designs developed by Rutgers included an option for adding pumping within each greenhouse zone to overcome friction headloss in the greenhouse distribution system. The pumps would maintain full flow through the main pipeline at the maximum provided by the head of the power plant pumps. This would be the same flow as would be in the line if the supply and return were directly connected at the greenhouse site, a flow calculated by the utility engineers at 30,000 l/min.

PERFORMANCE

During the first two full years of operation of the initial 1.1 hectare facility, PP&L contracted with Rutgers to monitor the performance of the heating system, (Manning et al., 1982, 1983, 1984). This effort evaluated each component of the heating system to verify its performance relative to design assumptions and to assess the overall system performance. The results provided information that could improve later designs and/or construction practices. The results of the first year of monitoring were reported by Manning et al., (1983). This initial monitoring program uncovered two significant discrepancies with design assumptions. First, the measured heat transfer rate from the pipes circulating warm water in the floor to the greenhouse air was only 60% of that anticipated and measured in earlier solar energy applications. The flooded floor was not properly leveled during construction, so that in many areas water did not cover the heat transfer pipes, which caused a reduction in heat transfer. This was an important observation and greater care in floor installation was taken in subsequent construction. Correcting this problem improved uniformity of environmental control as well as total energy delivery.

Second, the measured heat transfer from the overhead finned pipe was significantly less than indicated in calculations based upon the manufacturer's data. Analysis of the data provided revised heat transfer rate coefficients for use in subsequent system design. Some years later another manufacturer's data for finned pipe with identical specifications was obtained that closely matches the performance measured in the monitoring program. It would appear that the basic coefficients in the original manufacturer's data were not correct and predicted greater performance than the pipes could actually obtain.

A second full year of monitoring and evaluating thermal performance over two seasons, (Manning et al., 1982,1983, 1984) showed that the system as designed could provide 95% of the greenhouse requirements during periods when warm water from the utility was available. This performance in the 1983-'84 heating season was 96%, (Manning et al. 1984). During this period the pipeline was only fed from one of the two available cooling towers. When that unit was shut down for routine maintenance or an emergency there was no warm water available. Later, in 1986 the pipeline was extended to the second cooling tower, almost eliminating the periods when warm water was not available, since this generating station is a baseload provider for PP&L.

LATER DESIGNS

Campbell's Soup engineers designed and built a 2.4 hectare block for the Pepperidge Farm division to produce greenhouse tomatoes in 1983. For this block they used special type GLW Modine heaters designed for low temperature water sources. These units became commercially available after the first Bryfogle unit was designed in 1980. They elected to plumb these units in parallel with the floor heating system, which was essentially a copy of the original design. As these unit heaters have relatively low resistance to water flow the actual per hectare water consumption in this range was far larger than in the original 1.1 hectare greenhouse. In that original unit the actual water flow at the pressure provided in the pipeline by the utility pumping system was limited by the resistance to flow in the floor and finned pipe heat transfer loops. Measurements of water flow in this 2.4 hectare system showed that water flow was limited by the hydraulic resistance in the 30 cm submain, not the heat exchangers.

A later 1.1 hectare block built for Bryfogle in 1984 consisted of parallel use of water in pipes in a 10 cm porous concrete floor and similar type GLW Modine units for overhead heat. Again, as the Modine units had little built in flow resistance the water consumption per acre could be higher than in the original 1.1 hectare design. In retrospect, the design changes implemented after the original construction in 1980 actually reduced the efficiency of water use. As the total area had not yet approached the original anticipated pipeline capacity, this problem was not severe but it was recognized that it would limit potential future expansion. Suggestions to add pumping capacity to boost total flow were considered but the effectiveness of this proposed solution would be limited. Fortunately, there has been an opportunity to redesign the overhead heating system components that use power plant waste heat so that this problem can be completely corrected.

REDESIGN OF 1993

In rebuilding much of the Bryfogle range in 1993 a number of problems associated with both the waste heat delivery and back up heating system were addressed and solved. The engineers from Rutgers analyzed the details of the design of the former Pepperidge Farm range and considered a number of designs using the best information and available equipment as of 1993.

The approach in designing the rebuilt heating systems was somewhat different from the original 1980 approach. In 1980, actual hourly water temperatures and weather conditions from an earlier year were used as input to a simulation program to calculate energy balances, with the totals accumulated for the entire simulated heating season. Analysis of this data as well as data on warm water temperatures available during the first two heating seasons showed that there was no significant relationship between weather conditions and water temperatures. Therefore, in the 1993 design effort simulations were greatly simplified by assuming histograms for both weather conditions and available water temperatures based on actual operating data. The simulation is based on the assumption that the percentage of time the water is at each level of available temperature is the same for all weather conditions. This enables total seasonal contributions of the waste heat delivery system to be calculated directly based upon the heat transfer characteristics of the system and the greenhouse design.

Table 1
Hours per season at specified outdoor air temperatures

TEMP. °C	HOURS
-20.6	2
-17.8	10
-15.0	37
-12.2	86
- 9.4	11
- 6.7	18
- 3.9	272
- 1.1	428
1.7	529
4.4	405
7.2	320
10.0	240
12.8	372
15.6	147
18.3	106

Table 2
Percentage of time water temperature as specified

TEMP. °C	%
26.7	3
30.6	7
33.3	24
36.1	33
38.9	23
41.7	7
44.4	2
47.2	1

Using the above information, the seasonal contribution of any waste heat delivery design can be directly calculated for a desired greenhouse air temperature. For a heat exchange device the heat delivery for each condition listed in Table 2 can be calculated for a given water flow rate through that device, since the heat transfer characteristics of each is known. The temperature of the exit water can be calculated and used as the input temperature for another device if these are connected in series.

The first step in the redesign was to determine the feasibility of energy conservation methods which were a key element in the initial design. For comparative purposes, design factors were considered per each 64 by 8.5 m bay of greenhouse. Seasonal heat losses were calculated for operating temperatures of 15.6, 18.3 and 21.1 °C with and without movable insulation systems. These requirements with insulation systems are presented in Table 3. The annual savings of insulation, with energy valued at $8 per gigajoule, (GJ), are $2.20 to $3.10 per square meter per year. As the curtain material that achieves these savings also serves as a partial summer shade clearly the curtain system should be used. The design includes provisions for opening the curtain and supplying extra heat from the backup system under heavy snow conditions to promote melting.

With the energy saving curtain deployed the heat transfer coefficient from the greenhouse averages 2.9 w/m^2°C. The seasonal energy requirement for a single bay, based on the temperature distribution in Table 1, is calculated in the second column of Table 3 for typical operating temperatures given in the first column. The floor is the primary heat exchange system for the waste heat provided at the temperatures indicated in Table 2. The heat transfer coefficient from the floor system depends on the cropping system. Measured coefficients range from 3.5 w/m^2 °C for a floor covered with dry flats to 5.8 or more w/m^2 °C for spaced pots. The third and fourth columns of Table 3 show calculations of seasonal floor energy contributions for the three greenhouse air temperatures for the two floor conditions. The last two columns show the seasonal energy contribution calculated for one or two Modine Type 330GLW units in conjunction with a floor with spaced pots.

Table 3

Annual energy requirements and contributions per bay

Greenhouse Setpoint Temperature	Required heat per bay year	Floor heat provided with spaced pots	Floor heat provided with close flats	Add'l Heat from Modine 330 GLW 1st Unit	Add'l Heat from Modine 330 GLW 2nd Unit
°C	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*
21.1	385	221	139	117	44
18.3	325	233	153	80	12
15.6	267	226	158	39	2

With an estimated installed cost of $3,000 per unit heater, and with backup energy valued at $8 per GJ, the payback on the first unit heater ranges from 3 years at the higher set point temperature to 10 years at the lowest. The final design also allows hot water from the backup boiler to be circulated through the unit heater as supplemental heat in snow emergency situations, so at least one of these units was installed in each bay. Similar calculations were done, but not shown in the table, for adding unit heaters when the floor is covered with closely spaced flats. The economics of installing a second unit heater to extract additional heat from the waste water stream in that circumstance is only marginally economical, about a 5 year payback, for the highest operating temperature.

This design effort results in more efficient use of the available water and in better performance of both the waste heat and backup heat delivery systems. The major changes from the original 1980 design involved switching from finned pipe to the Modine Type 330GLW units for utilization of waste heat overhead. It was found, as a result of careful systems analysis and by simulation of a number of possible designs, that much more efficient use of the waste heat resource in the former Campbell's sections would be achieved if water were run through the Modine units in series with the floor rather than in parallel as had been the case. There is a slight reduction in total heat delivery to the greenhouse under extreme weather conditions or when the supply water is relatively cool, but the additional backup heat required as touchup on an annual basis is modest. Figures 1 through 3 show various configurations that achieve lower flow rates without significantly reducing heat delivery.

The exact pattern of use of water in the greenhouse units varies from one area to another based on accessibility of the floor piping during reconstruction. The most efficient design from the standpoint of the use of the water consists of all Modine units in series with the floor, whether these units be on one side of the greenhouse or both. In this configuration water consumption appears to be on the order of 106 l/min per bay, or about 1870 l/min per hectare. While some sections currently have Modines on one side of the greenhouse plumbed in parallel, this could be changed to series when necessary.

THE GROWER'S PERSPECTIVE

The project's major successes:

When Bryfogle and PP&L presented the grant for partial project support to the Appalachian Regional Commission, the commission was looking for a successful project to be supported by tax dollars that would provide jobs and truly conserve energy. Ten years later it turned out that this was the only project they ever funded that worked as planned and in fact succeeded beyond their wildest dreams. The success of the project has actually led to significant problems today, which are discussed later. Dr. Pfeiffer's proposal required abandoning the family greenhouse location in Muncy and relocating to the waste heat site in Washingtonville. The grant money and PP&L backed loans provided the opportunity to prepare facilities for the future of potted plant greenhouse operations. While the use of waste heat has provided a significant advantage, the opportunity to rebuild and modernize facilities has been the true launching pad to the current success of the operation. The advantages in the new facility at Washingtonville include improved environmental control systems, larger open growing areas, and better layout of growing and working areas, which enable implementation of management improvements. These improvements also led to changes in production, so that more of the greenhouse area is used throughout the year rather than seasonally.

Designing for utilization of the waste heat resource dictated a major reliance on floor heating and the use of energy conserving overhead curtain systems that could also be designed for partial shading in hot weather. Fifteen years of operation demonstrate that using waste heat provides the following major advantages:

- The financial savings due to reduced heating costs pay for half the total construction costs.
- The waste heat resource is essentially constant over the year, and the thermal storage of the floor system stabilizes heating costs so the seasonal variations are leveled off.
- There is an incentive to construct better greenhouses designed for year round crops. This enables the facility to provide a higher percentage of year round jobs, stabilizing the work force and providing a higher level of expertise and performance than is possible with .seasonal employees.

Some of the key statistics indicating the success of the total project including the improved system design and waste heat utilization are:

- The greenhouse area has grown from 1.1 hectares in 1980 to 7 hectares in 1996.
- Income to PP&L has grown from $27,000 a year to over $200,000. The original budget for pipeline construction was $300,000 (Pfeiffer and Bryfogle, 1979).
- The greenhouse business provides $60,000 per year in local property taxes.
- The payroll puts over $2,000,000 each year into the local economy.
- Employment has grown from 5 full time and 25 part time workers to over 55 full time and 210 part time jobs.
- If the business climate remains stable there could be an additional 8 hectares of greenhouses over the next 8 years.

Major problems overcome:

While the construction of a new facility provided many advantages, some of which are covered above, there were significant problems that were not anticipated and had to be overcome. A major problem at the early stages related to water quality. It turned out that the groundwater at the Washingtonville site is basically unsuitable for growing quality plants. It took about three years in a very expensive learning process to work around these problems. Retention basins were installed to capture runoff from the roofs and this provided the basis for the solution of the problem. The nutrition program was adjusted to compensate for the lack of trace elements in the rainwater. Disease problems associated with the storage of water in clay ponds cost a great deal in lost or damaged crops until solutions were found.

The site is in a remote, rural area so there have been significant difficulties in attracting employees to travel the long distances to work. The opportunity to provide a higher percentage of year round employment has been helpful in this regard. The remote location also contributes to increased susceptibility to vandalism and theft.

The greenhouse operation has attracted intense scrutiny and oversight by the Pennsylvania Department of Environmental Regulation (DER) because of its proximity to and connection with the utility and the high profile of the project. While this has caused a number of problems, the long term advantage is that it has forced the adoption of a number of operating techniques to control environmental impacts at this site that are likely to become mandatory for greenhouses everywhere in the next century.

There have been two major calamities, both of which have been overcome successfully but at great effort. In the summer of 1990 the office and service building adjacent to the first block of greenhouses was destroyed by arson. These facilities were rebuilt but there was significant damage to a portion of the floor heating system in the adjacent greenhouse section. In 1993, 28 inches of snow and 50 mph winds caused the collapse of 89% of the greenhouse area. This has now all been rebuilt with improved structural components and the improvements to the environmental control system discussed elsewhere in this paper.

Current problems:

Current problems appear to stem from a number of changes in the utility industry in general and PP&L in particular that have altered the perspective of the greenhouse facility from the utility standpoint. Retirements have reduced the institutional memory of the roots and basic objectives of the project in the senior management levels. Changes in regulation and competitiveness in the utility industry have shifted the focus of top management. It seems that currently the focus has shifted towards short term planning as the utility industry becomes more competitive. As a result little or no thought is being put into capitalizing the long term benefits to themselves and the surrounding economy or of maximizing the use of the wasted resource they possess.

There seems to be a fear of making an unpopular decision, and since there is less understanding of the potentials and problems associated with the greenhouse operations, decision making in that area has bogged down. What was once perceived by PP&L management as an innovative and mutually beneficial relationship now appears to be regarded as a potential problem. Clearly, the greenhouse operation, with large amounts of employee car and truck traffic at peak production times, and a highly visible infrastructure provides a less "neat and tidy" image than acres of leased cornfields. Also, there has never been significant likelihood that greenhouse operations could make use of more than a small portion of the wasted heat resource that could potentially be provided by the utility. This may reduce somewhat the positive public relations impact in the eyes of utility management.

In the final analysis the relationship with the utility in a project that has turned successful beyond anyone's dreams appears to be going sour. Decision making has slowed dramatically. Questions that used to be resolved with a phone call now require a year to decide. In the early years of the project all the parties cooperated closely. Should this relationship deteriorate from indifferent to adversarial, significant opportunities for further advances will be lost. Hopefully, PP&L management's interest in the project will revive and it will realize its future potential.

FUTURE POTENTIAL

Without changing the concept of water use beyond that developed in the 1993 redesign it should be possible to connect up to 16 hectares to the existing 50 cm pipeline. This assumes that pumping can be used to overcome friction in submains and distribution systems at the design water flow rate of 30,000 l/min. It should also be noted that there is the possibility to run from one greenhouse block and then through another in series connection from the waste heat water source. This would reduce the per hectare contribution of energy from the waste heat source when the weather is extremely cold and/or the waste heat is at relatively low temperature. However, this impact would be negligible on the first house in series and on the second house during the spring or fall seasons. As not all area is used throughout the coldest months this is an option that could be considered as total connected acreage gets above 16 hectares.

It should also be noted that many of the greenhouse blocks have a flooded floor heat delivery system with a massive thermal storage capacity. The dry porous concrete floors have less thermal capacity, and the ebb-and-flood irrigation systems have an intermediate thermal capacity. As greenhouse acreage increases it is possible to implement control strategies whereby energy can be banked in daytime to extend heating at night. Recent research on feedforward control indicates how to enhance this effect. A recent publication, (Takakura et al., 1994), develops the concept of this topic, but there has not been a commercial demonstration of this concept to date.

The most effective use of the waste heat resource will be achieved as the acreage is increased and the designs follow the principles of optimization discussed above. Careful system design not only improves the use of the capital investment from the standpoint of the greenhouse operator but also maximizes the cooling of the water before returning it to the power plant.

FINANCIAL

In the original conceptual discussions involving PP&L and Rutgers the idea of basing annual pipeline use charges on peak capacity was agreed upon as a strategy that would be both fair and most likely to promote further development based on efficient water usage. Based on PP&L estimates of 30,000 l/min flow and pipeline construction, maintenance costs that require annual charges of $100,000 to fully recover costs with profit at the then current utility rate, and the Rutgers design of the original greenhouse calling for 3740 l/min per hectare, the utility set an annual charge of $12,350 per hectare.

The higher charge of $18,525 per hectare subsequently set for the Campbell's block was based upon the anticipated higher water flow requirement of their original design. Rutgers was never involved in discussions with PP&L about charges for that component of the facility but the concept is consistent with earlier discussions. The redesign of the former Campbell's block in 1993 substantially reduced peak water requirements in that section. Subsequent designs are more efficient than the first 1.1 hectare block so it makes sense to reassess per hectare rates based on the original assumptions of total pipeline charges when fully utilized of $100,000 per year based on per hectare peak water flow.

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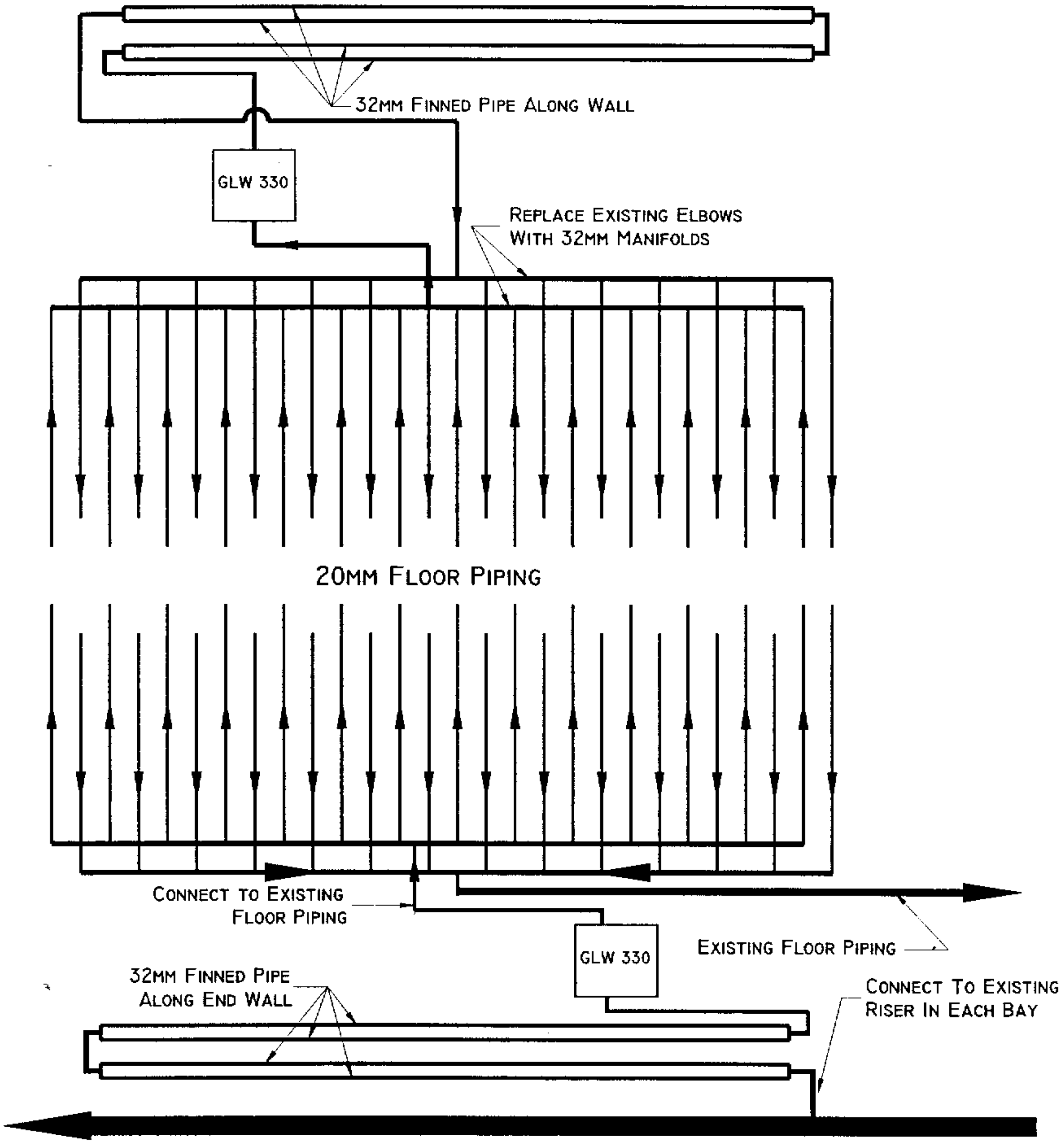
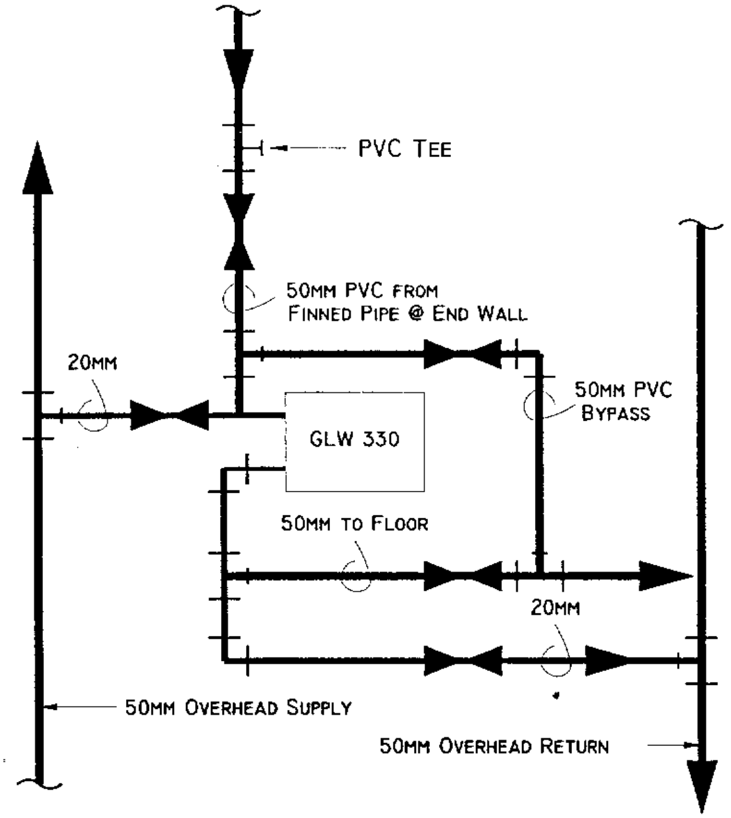
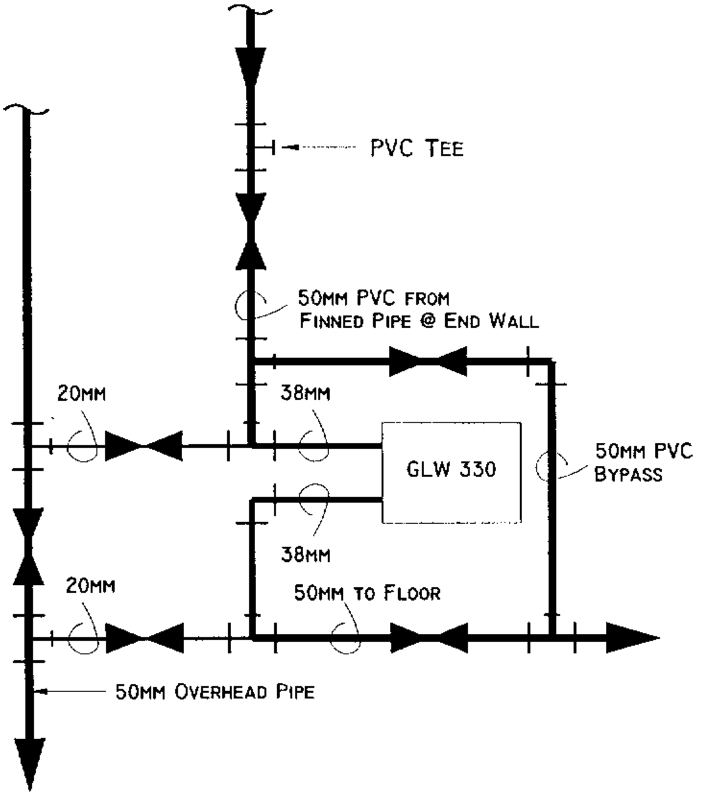


FIG. 1: FLOOR PIPING WITH TWO UNIT HEATERS IN SERIES



Connection Between Supply and Return



Connection to Supply Piping

Fig. 2: Unit Heater Waste Heat and Backup Piping

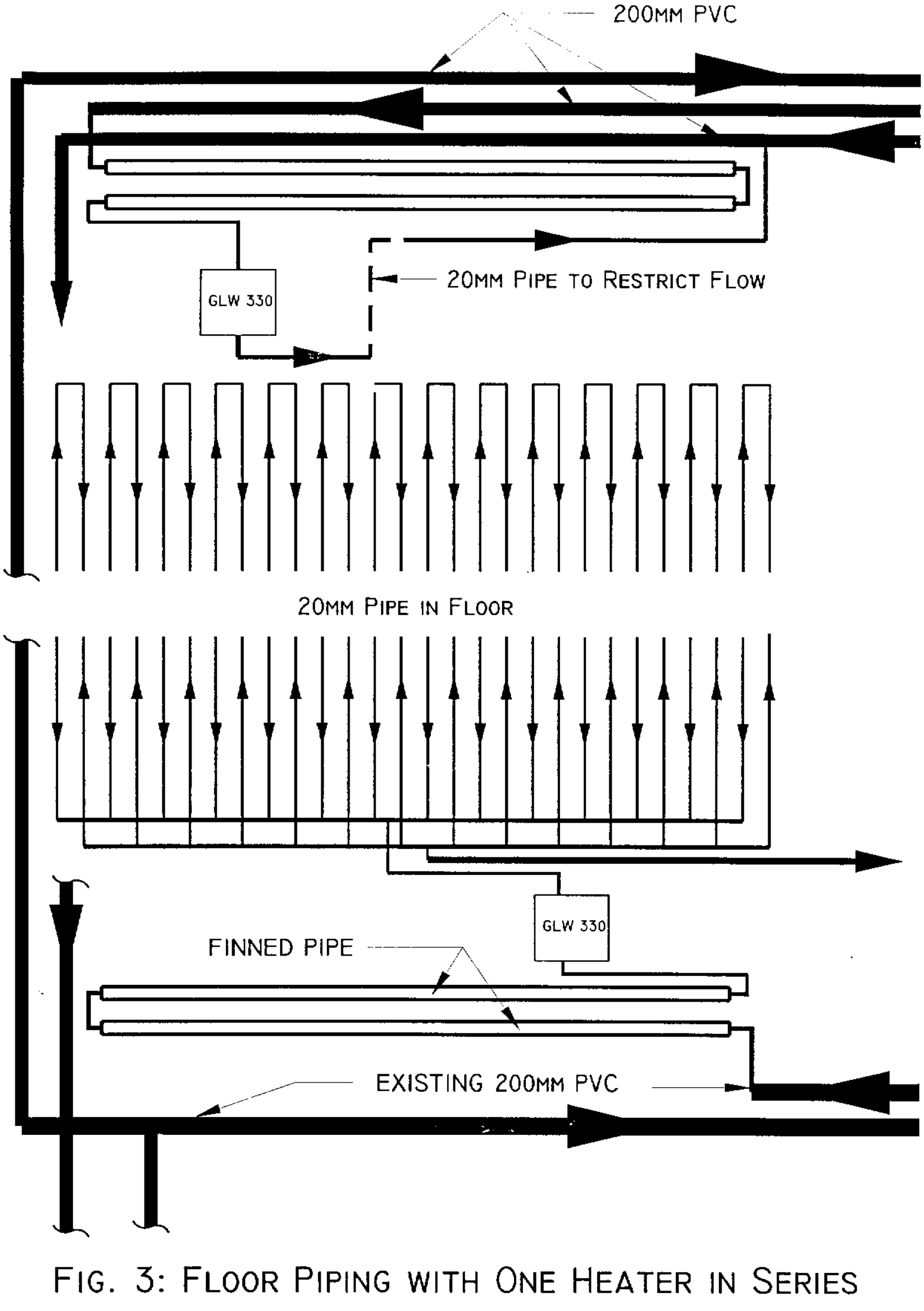


FIG. 3: FLOOR PIPING WITH ONE HEATER IN SERIES