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STUDY OF THE OPERATION OF A WASTEHEAT GREENHOUSE

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SUMMARY:

This paper reports the results of the second year of data collection at the Power Plant, Inc., waste heat greenhouse in Washingtonville, Pennsylvania.

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STUDY OF THE OPERATION OF A COMMERCIAL WASTE HEAT GREEENHOUSE

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Introduction:

The Montour County Generating Station operated by Pennsylvania Power and Light in Washingtonville, Pennsylvania currently supplies warm water to almost 5 hectares of greeenhouses. From late 1981 to early 1984 the first greenhouse constructed at the site by Ken Bryfogle, of Power Plants, Inc., has been monitored to determine energy balances and establish heat transfer rates of the system components. The results of the first full heating season of this study were published in a previous paper.

Description of 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.

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 1.9 cm polyethylene pipe embedded in the gravel

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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 power plant. In the fall of 1983 this pipeline was extended to connect to the second of the two cooling towers at the plant.

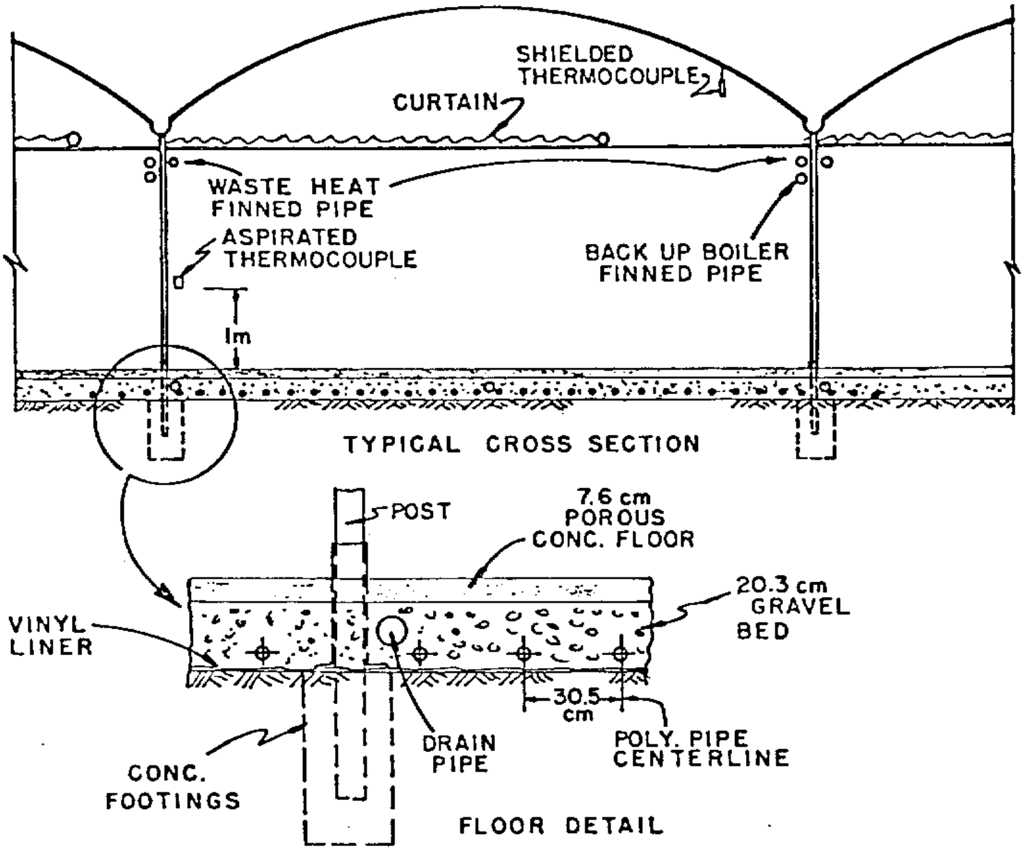

Fig I

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 100m 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 4.3m centers distributes the water flow evenly through the floor.

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

Results:

Accurate determination of the thermal mass of the greenhouse floor and heat transfer rates from the pipes embedded in the floor to the water in the floor and from floor water to greenhouse air were primary objectives of the second year of data collection. Previous data (Manning et al., 1983) had shown that the total heat transferred from the floor was less than expected. Four "aspirated" water temperature sensors, created by placing a thermocouple in the outlet of a pump drawing water from the flood floor, were used to ascertain floor water temperatures during the entire heating season.

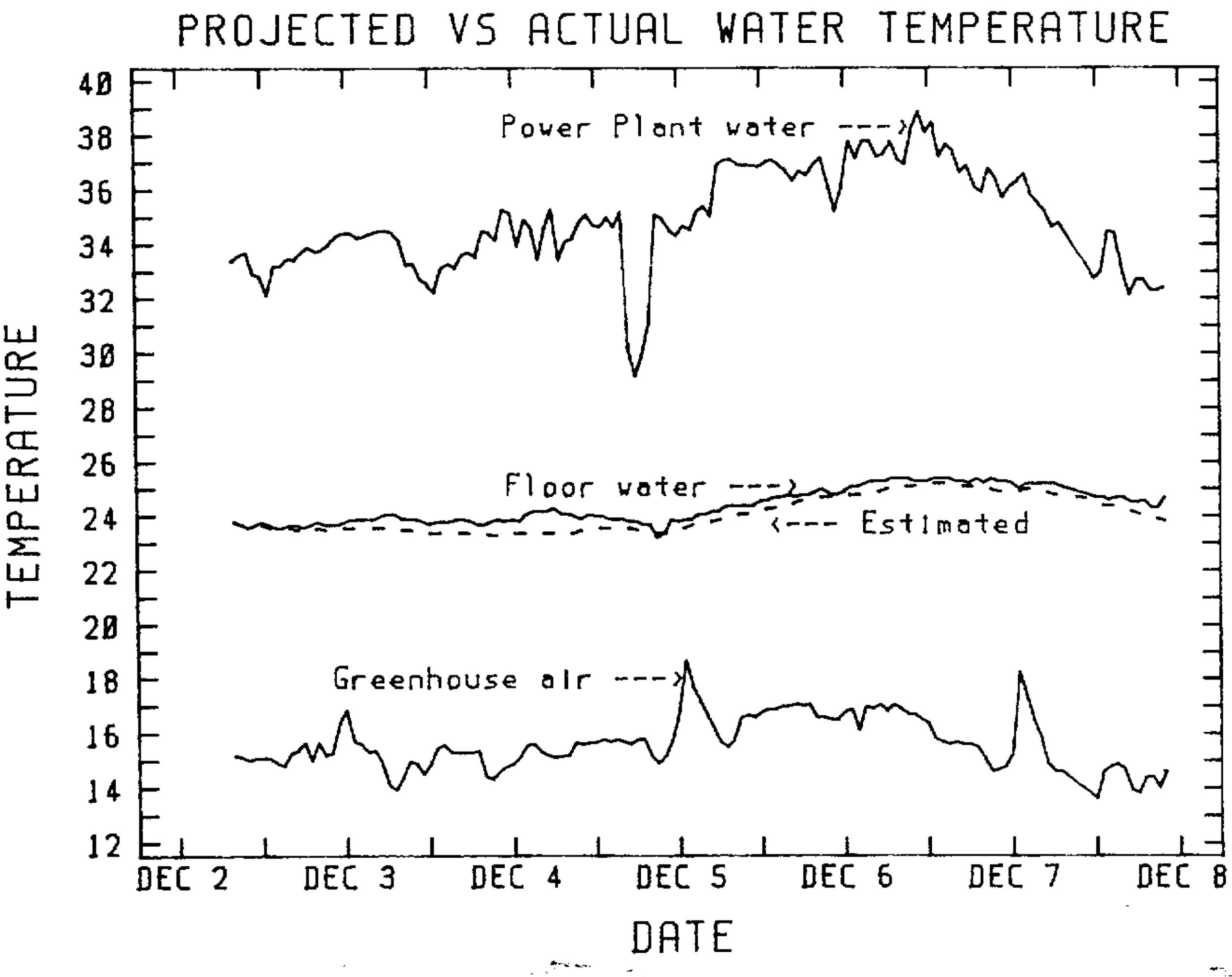

FIGURE 2

If heat loss downward is neglected the heat transfer rate can be calculated by measuring the heat input to the floor, the average temperature difference between floor water and greenhouse air and the change in water temperature over a period of time. Using data from December 2 to December 8, 1983 (Figure 2) provides a value of $7.2 W/m^2K$ for the heat transfer rate between the water and the floor. At the time the floor was about 50% covered with pot plants, and this heat transfer rate is consistent with previously obtained values in similar greenhouses. For this same period the difference in temperature between the water in the pipes and the water in the floor averaged $7.3^{\circ}C$ while the difference between the floor water and greenhouse air averaged

8.3°C. The heat transfer from the pipe to the water therefore equals 8.2W/m^2K. The net heat transfer rate, from water in the pipe to the greenhouse air, is (7.2 x 8.2)/(7.2 + 8.2), or 3.8W/m^2K. Figure 2 shows a theoretical estimate of floor water temperature based on calculated heat transfer rates and a starting floor water temperature of 24°C. The ratio of the temperature differences between water in the pipes and water in the floor and water in the floor and greenhouse air varied from 0.65 to 0.87 and averaged 0.73 for the heating season. The variation can be attibuted primarily to changes in the floor heat transfer rate with different crops and variation in flow through the pipes due to changes in the pipeline pressure. Floor water level remained fairly constant throughout the period and should not be a factor. From this ratio we can determine that the net heat transfer rate (from water in the pipe to greenhouse air) is between 3.2 and 4.3W/m^2K, and that the average rate is approximately 3.6W/m^2K. Since heat transfer rates from floor water to greenhouse air are consistent with previous results (Roberts et al., 1980), low heat transfer rates from the pipe to the water must be the main cause of the low overall heat transfer.

The overhead curtain system was investigated in greater detail to ascertain what affects the heat transfer rate across it. Since some of the curtains did not seal well against the gutter, the effect of a small opening between the gutter and curtain was investigated. The influence of convective currents caused by hot water flowing through the finned pipe adjacent to the gutter was also studied. The results of these tests are shown in Table I. The energy savings under each of these conditions were estimated by dividing the temperature difference between the air at the plant canopy and the area above the curtain by the temperature difference between the air at the plant canopy and outside.

	TEMPERATURE (°C)			
	Outside	Above curtain	Plant canopy	Savings (%)
Overhead waste heat on, curtain sealed	-7.4	8.9	15.0	27.3
Overhead waste heat on, curtain open 5 cm	-7.9	10.0	14.4	19.7
Overhead waste heat on, backup heat on, curtain sealed*	-7.9	11.9	15.4	15.0

*Pipe water temperature = 70°C

TABLE 1

Experimental Results and the Design Process:

Figure 3 shows the relationship between temperature difference and hours of occurrence during the heating season, based on three years of data from the Washingtonville site. From this chart we can conclude that a heating system capable of maintaining a temperature difference of 23°C between greenhouse air and outside ambient will provide 95% of the annual greenhouse heating requirements, or a system capable of maintaining a 20°C difference will provide 90% of the needed energy. Having determined the heat transfer rates of the heating components and using average temperature values, a rough estimate can be made of the energy provided by a specific heating system. For Washingtonville, the average temperature of water in the pipes in the floor is 33°C and the greenhouse nighttime temperature setting is usually around 16°C. With a heat transfer rate of $3.6 W/m^2 K$ from the water in the pipe to the greenhouse air, and an effective heat transfer rate of 4.0W/K per square meter of floor area, the floor heating system can maintain a temperature difference of 15.3°C. The finned pipe can provide 30.5W per square meter of floor area, and can therefore maintain an additional temperature difference of 7.6, so that the waste heat system can maintain approximately 23°C difference between greenhouse air and outside. From Figure 3, the heating system should be capable of providing 95% of the total greenhouse needs.

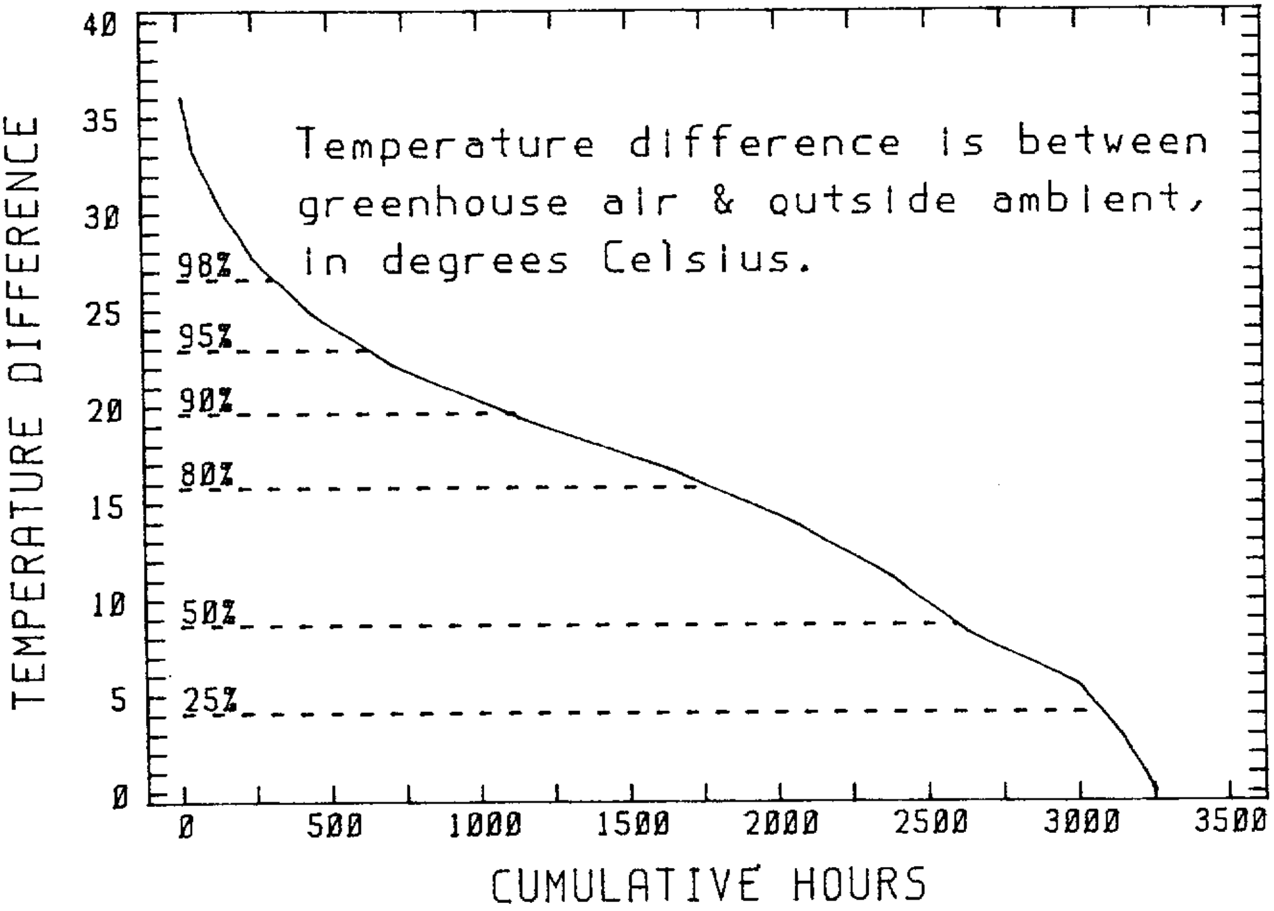

FIGURE 3

Examination of Figure 4 reveals one of the problems with this analysis. The power plant water temperature varies considerably, and in extremely cold weather the temperature is often raised to prevent freezing in the cooling tower. Also, as mentioned above, heat transfer rates vary according to type of crop and water flow rates. The percentage of heat provided also depends on the availability of power plant water, and the time of year at which outages occur. Since the pipeline was extended to the second cooling tower in late 1983, power plant outages are much less of a factor in the Washingtonville greenhouse. For the 1983-84 heating season warm water was available about 96% of the time, and most of the interruptions occurred in the fall. A full evaluation of a heating system design should consider these factors, and a model of the entire system is perhaps the best means of performing a complete evaluation (Manning and Mears, 1981).

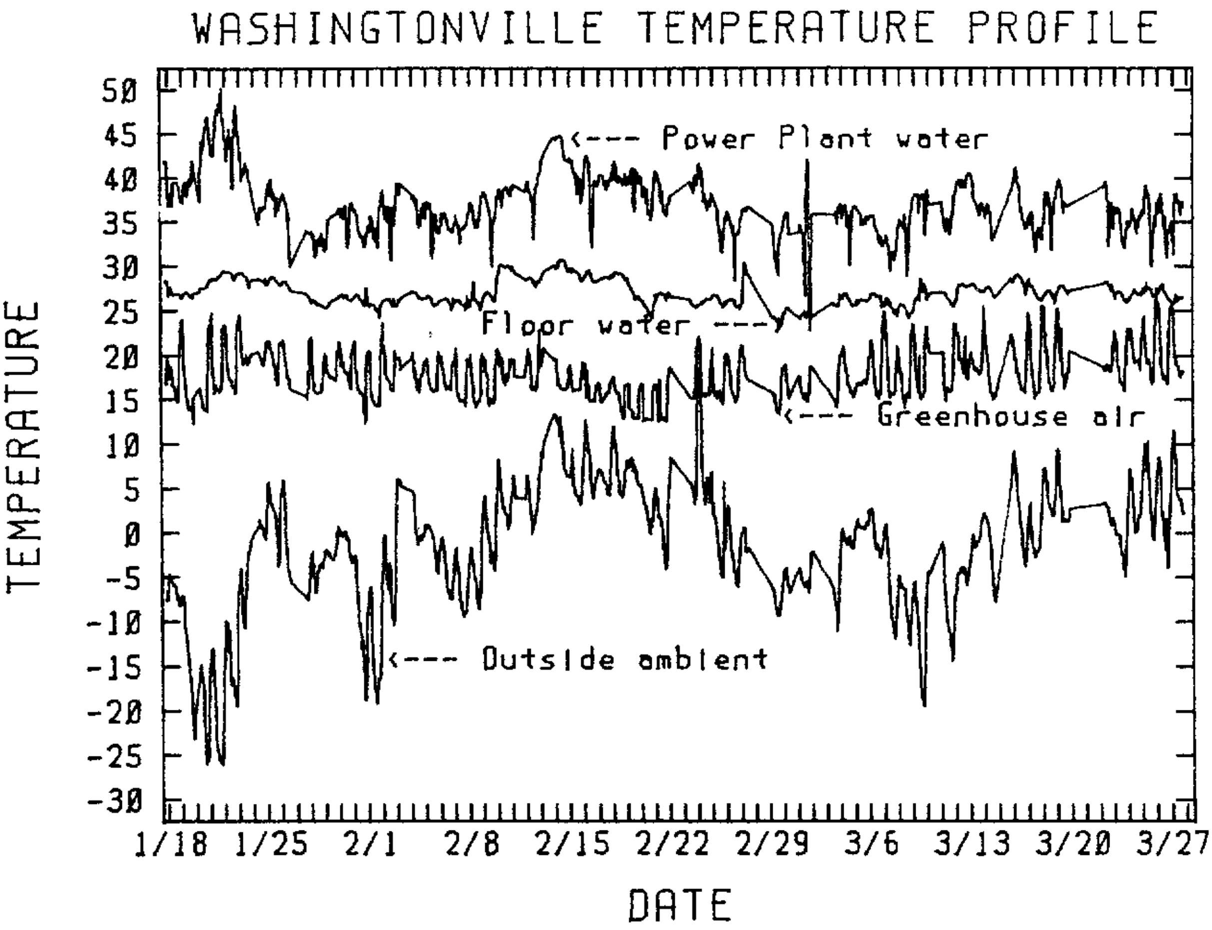
WASHINGTONVILLE TEMPERATURE PROFILE

FIGURE 4

Conclusions:

The greatest problem observed in the course of this study has been the low heat transfer through the flooded floor. This problem appears to be mostly due to poor heat transfer into the water in the floor from the water in pipes. The most probable causes for this are fouling of the pipes, stratification of water in the floor and uneven distribution of water due to variations in level of the floor. Continuous stirring of the water in the floor and routine cleaning of pipes can help improve the heat transfer, although neither of these measures can affect the uneven distribution of water. However, the most promising solution is to introduce power plant water directly into the floor, which should increase heat transfer by at least 60% (from 3.6 to $5.8 W/m^2K$).

As can be seen from Figure 4, the incoming water temperature frequently dips 5^oC or more. Although these dips are of short duration and generally do not go below the temperature of the water in the floor in a greenhouse with a higher ratio of floor heat transfer to thermal mass of the floor an automatic shutoff valve to eliminate these dips could increase the thermal performance of the floor.

The results concerning performance of the thermal curtains clearly indicate the necessity of attaining a good seal at the edges of the curtain. If the curtains are made of a porous material measures to reduce the convective flow of air through the curtain are important. These include modulating heating pipe temperatures to meet demand, placing pipes near the tail edge of the curtain rather than the leading edge, placing some kind of convective barrier above the pipe, and using steel tubing rather than finned pipe wherever possible.

The results of this study demonstrate the engineering feasibility of designing a greenhouse to utilize warm water (averaging 40°C) for heating. Proper design and construction of a warm floor are clearly essential in order to realize the greatest benefits from this design. In particular, the floor should be level, should have stirring pumps to mix the water and should have a mechanism for cleaning the embedded pipes. An alternative is to circulate warm water directly through the floor, which has the two-fold advantage of eliminating the pipes in the floor and substantially increasing the heat transfer. The long term effects of silt accumulation and fouling in this situation have not been investigated, and a floor used in this way should incorporate mechanisms for reducing these problems.

Optimization of the performance of this type of greenhouse can best be obtained by improved control of the various heating systems. In light of the fact that the pipeline to the greenhouses represents a substantial cost, automated controls that reduce the peak flow of water per unit area while maximizing the heat extracted from the water will improve the economics of the use of waste heat. As the greenhouse area in Washingtonville expands the need for better management of the warm water becomes increasingly clear, both to maximize the benefits for individual greenhouses and to reduce the adverse effects of one greenhouse upon the other.

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