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GREENHOUSE PRODUCTION OF BEDDING AND FOLIAGE PLANTS WITH INDUSTRIAL HEAT

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ABSTRACT

Potential beneficial use of industrial waste heat for the production of bedding and foliage plants was evaluated via use of conventionally and warm water heated greenhouses in Fort Valley, Georgia. Each greenhouse was 9.1 m X 21.9 m (30 ft X 72 ft) and a plastic covered quonset. The research greenhouse was heated and cooled using simulated warm condenser cooling water, while the control greenhouse had conventional heating and cooling in the 9-month test program. During 1979, cultivars of 10 leading ornamental bedding plants, 8 species of foliage plants, and tomatoes as bedding plants were studied for growth rate, survivability, time of flowering, and susceptibility to disease in the humid greenhouses.

No statistically significant difference in growth rate for 7 of 10 ornamental and 2 of 8 foliage plants was observed in the two greenhouses. Tomatoes, coleus and geraniums grown in the conventional greenhouse had statistically significant higher growth rates. Syngonium podophyllum and Philodendron pertussum grown in the waste heat research greenhouse had statistically significant higher growth rates. Ornamental bedding plants grown in the conventional greenhouse flowered approximately 7.6 days earlier. No significant difference in survivability among foliage plants and 8 of 10 ornamentals was seen in either greenhouse. Browallia and coleus survived better in the conventional greenhouse. No diseases were evident in either greenhouse.

Heating and cooling of the waste heat research greenhouse was satisfactory, despite the fin-tube heat exchanger being oversized for the available warm water flow. Environmental control was adequate; at no time was condensation observed on the foliage of plants grown in either greenhouse. Preliminary economics indicate that industrial waste heat can be an attractive alternative to natural gas and fuel oil for greenhouse heating.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

Btu	--	British thermal unit
^oC	--	degrees Celsius
^oF	--	degrees Fahrenheit
ft	--	foot
gal	--	gallon
gal/min	--	gallons per min
Gj	--	gigajoules (one billion joules)
g	--	gram
hr	--	hour
in	--	inch
l	--	liter
l/min	--	liters per minute
l/s	--	liters per second
Mj	--	megajoules (one million joules)
MW	--	megawatt
m	--	meter
m/s	--	meters per second
mph	--	miles per hour
MBtu	--	million British thermal units
No.	--	number
ft^2	--	square foot
in^2	--	square inch
m^2	--	square meter
Tj	--	terajoules (one trillion joules)

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SECTION 1

INTRODUCTION

BACKGROUND

Water is used in the power plant industry for cooling purposes and energy added to this water is described as waste heat. In the past, the normal procedure has been to dump discharged cooling water coming from power plants back into rivers, lakes and cooling ponds where the energy added is dissipated. Most recently, to prevent adverse environmental impacts of waste heat and to prevent large water withdrawals associated with harm to aquatic life, the power plant industry has been forced to build expensive cooling towers.

If means can be developed so that this warmed water could be utilized to heat and cool greenhouses and extend the growing season of certain horticultural and field crops, it would help conserve energy while improving water quality. Three other advantages are (1) a normal waste product would have economic potential to the power plant, (2) a reduction in the cost of crop production could be passed on to the consumer, and (3) the country would realize a slight-to-moderate reduction in thermal pollution depending on size, kind of industry and location.

The Environmental Protection Agency estimates that the U. S. will require approximately 757 billion liters (200 billion gallons) of fresh water daily to cool the condenser steam of power plants required to produce the thousand billion kilowatt hours needed annually by 1980 (2). Such water will be essentially free of contaminants, and it will be discharged at 29^{o} to 49^{o}C (85^{o} to 120^{o}F).

The annual quantity of waste heat presently available in the U. S. is approximately 10,500 quadrillion joules (10 quad* Btu) equivalent to 254 gigaliters (1.6 billion barrels) of fuel oil (8). This represents an annual amount of energy slightly less than 20% of all the energy used annually in 1971. However, this is a low-grade (low temperature) form of energy, and opportunities to use it beneficially are limited. Within 30 years, the electrical power industry will require the disposal of about 21 quadrillion joules (20 trillion Btu) of waste heat per day (6). One nuclear power plant having a 1,000 MW capacity can supply enough waste heat to accommodate 400 hectares (1,000) acres of conventional greenhouses (9).

Greenhouses require large amounts of energy to maintain adequate temperatures for crop production. The amount of energy required will vary with location, type of greenhouse, energy conservation measures, and crop. In the Tennessee Valley area, the energy required for greenhouse crop production may exceed 13.1 Tj/hectare (12.4 billion Btu/hectare) or 5.3 Tj/.4 hectare (5 billion Btu/acre) and in Minnesota 19.3 Tj/hectare (18.3 billion Btu/hectare) or 7.8 Tj/.4 hectare (7.4 billion Btu/acre) (4). The U. S. Department of Agriculture reported in 1974 that

*1 quad = 10^{15}

108,914,015 m^2 (357,329,446 ft^2) or 3,320 hectares (8,203 acres) were used for greenhouse space (5). By conservative estimates, the greenhouse industry has grown by 5 percent each year since 1974 with a current estimate of 4,237 hectares (10,469 acres). The average energy requirement for greenhouses in the U. S. can probably be estimated by using the average Btu requirement for greenhouse production in Minnesota and the Tennessee Valley area which is approximately 16.1 Tj/hectare (15.3 billion Btu/hectare) or 6.5 Tj/.4 hectare (6.2 billion Btu/acre). Based on this assumption, the greenhouse industry uses in excess of 66 quadrillion joules (64 trillion Btu) annually. The fuel equivalent of this amount of energy could be beneficially used in the U. S. alone by utilizing waste heat. In addition, should most of the greenhouses throughout the world eventually change to waste heat, the energy saving will be even more substantial on a global scale.

Currently, 30 to 40 percent of the cost of greenhouse crop production is used for energy and is increasing, while natural gas and fuel oil supplies are becoming less available for greenhouse heating. Since most greenhouses are heated with natural gas, the present cost for 67 quadrillion joules (64 trillion Btu) at $3.04/Gj ($3.20/million Btu) for natural gas exceeds $204 million annually. The cost of 67 quadrillion joules (64 trillion Btu) supplied by No. 2 fuel oil at $6.45/Gj ($6.80/million Btu) would exceed $433 million. Using waste heat at $.96/Gj ($1.02/million Btu), the cost of 67 quadrillion joules (64 trillion Btu) would be $61.4 million. In addition to conserving fossil fuels, the cost for energy could be reduced by 232 percent or $142.6 million over the use of natural gas and $371 million or 605 percent over the use of No. 2 fuel oil if waste heat was used, while at the same time environmental pollution would be reduced through the reduced combustion of fuel.

OBJECTIVES

This study investigated the potential beneficial use of industrial waste heat for greenhouse production of bedding plants, cut flowers, and foliage plants. The research facilities consisted of a conventional greenhouse and a greenhouse modified to use simulated waste heat.

The major overall objectives of this research were: (1) to test a feasible way to utilize waste heat, thereby conserving energy, (2) to test the suitability of the greenhouse environment for the production of ornamental and vegetable bedding crops, cut flowers and foliage plants, and (3) to evaluate the overall economics of the system. The more specific and detailed objectives are listed below:

Horticultural Objectives

1. To compare the quantitative growth data between the crops grown in the control greenhouse and the crops grown in the simulated waste heat greenhouse on the production of bedding plants, foliage plants and cut flowers.

2. To evaluate the incidence of diseases between the crops grown in the control greenhouse and crops grown in the simulated waste heat research greenhouse under high relative humidity (90-100%) conditions.

Economic Objectives

1. To compare the annual cost of production for each crop produced in the conventional greenhouse and the simulated waste heat greenhouse.

2. To evaluate the economic implications of two production management systems in both greenhouses.

3. To conduct limited market tests to determine consumer acceptance of waste heat greenhouse production.

Engineering Objectives

1. To compare controlled-environment data of the control greenhouse with that of the simulated waste heat greenhouse for the entire year with reference to heating, cooling and dehumidification.

2. To determine the responses of the control greenhouse with that of the simulated waste heat greenhouse resulting from changes initiated by a relatively sophisticated control system as well as changes from external pertubations.

A DESCRIPTION OF THE RESEARCH FACILITIES

The research facilities consisted of two quonset-type plastic greenhouses, each 9.1 m X 21.9 m (30 ft X 72 ft). The plastic covering for each greenhouse consisted of a double layer of Monsanto 602-6 mil polyethylene plastic. One greenhouse served as a control and the other greenhouse served as the waste heat research greenhouse.

The control greenhouse was not modified in any manner. It has a climate control system equipped with fans, shutters, plastic convection tube, two natural gas heating units, and controls to provide a suitable greenhouse environment.

In the control greenhouse, cooling is provided by an evaporative Kool-cel* pad located at one end of the greenhouse and two exhaust fans located at the opposite end of the greenhouse. Heat is supplied by two natural gas heaters with a heating capacity of 111 Mj (105,000 Btu) per hour. The heat is disseminated by a fan through a 0.61 m (24 in) polyethylene convection tube with punched holes to bring about even distribution of heat throughout the greenhouse.

*Trade Mark, ACME Engineering and Manufacturing Corporation

The waste heat research greenhouse, on the other hand, is modified. Both heating and cooling are supplied by evaporation from a 4.3 m X 2.7 m (14 ft X 9 ft) Kool-cel pad through which air is circulated by two large exhaust fans. For cooling, air is drawn through the Kool-cel pad and discharged directly outside. Exactly 0.61 m (2 ft) of the Kool-cel pad is located in the attic plenum. Intake louvers are located at one end of the attic plenum. Since much of the heat from warm water is dissipated in the top 0.61 m (2 ft) of the Kool-cel pad, much of the heat is discharged out of the attic before it reaches the growing area of the greenhouse. This modification in the design of the waste heat research greenhouse permits the use of warm water during the summer months when the temperature of industrial waste water, especially from power plants, is at its highest; and yet, it will provide excellent evaporative cooling in the growing area of the greenhouse.

Heating in the waste heat research greenhouse is provided by recirculating air through the attic plenum over the Kool-cel pad and/or the fin-tube system.

Simulation of waste heat for the waste heat research greenhouse is supplied by a 105 KW electric water heater (boiler). The simulated temperatures of water were based on the average monthly temperatures of effluent condenser cooling water of each month of the year as obtained from the Tennessee Valley Authority's Browns Ferry Nuclear Power Plant located in Northern Alabama.

Located 1.2 m (4 ft) downstream from the Kool-cel pad is the fin-tube system. The fin-tube system consists of two staggered rows of 0.05 m (2 in) radiation tubes 5.49 m (18 ft) long. The fins on the tubes are 0.1 m X 0.1 m (4 in X 4 in). Warm water is pumped through this system of fin-tubes to provide a dry heat exchange and to aid in dehumidification.

The floor in each greenhouse consists of a concrete walkway 1.2 m (4 ft) wide located in the center of the house with the remaining part of the floor being covered with 0.1 m (4 in) of gravel.

Figure 1 and Figure 2 are schematic representations of the waste heat research greenhouse and control greenhouse, respectively.

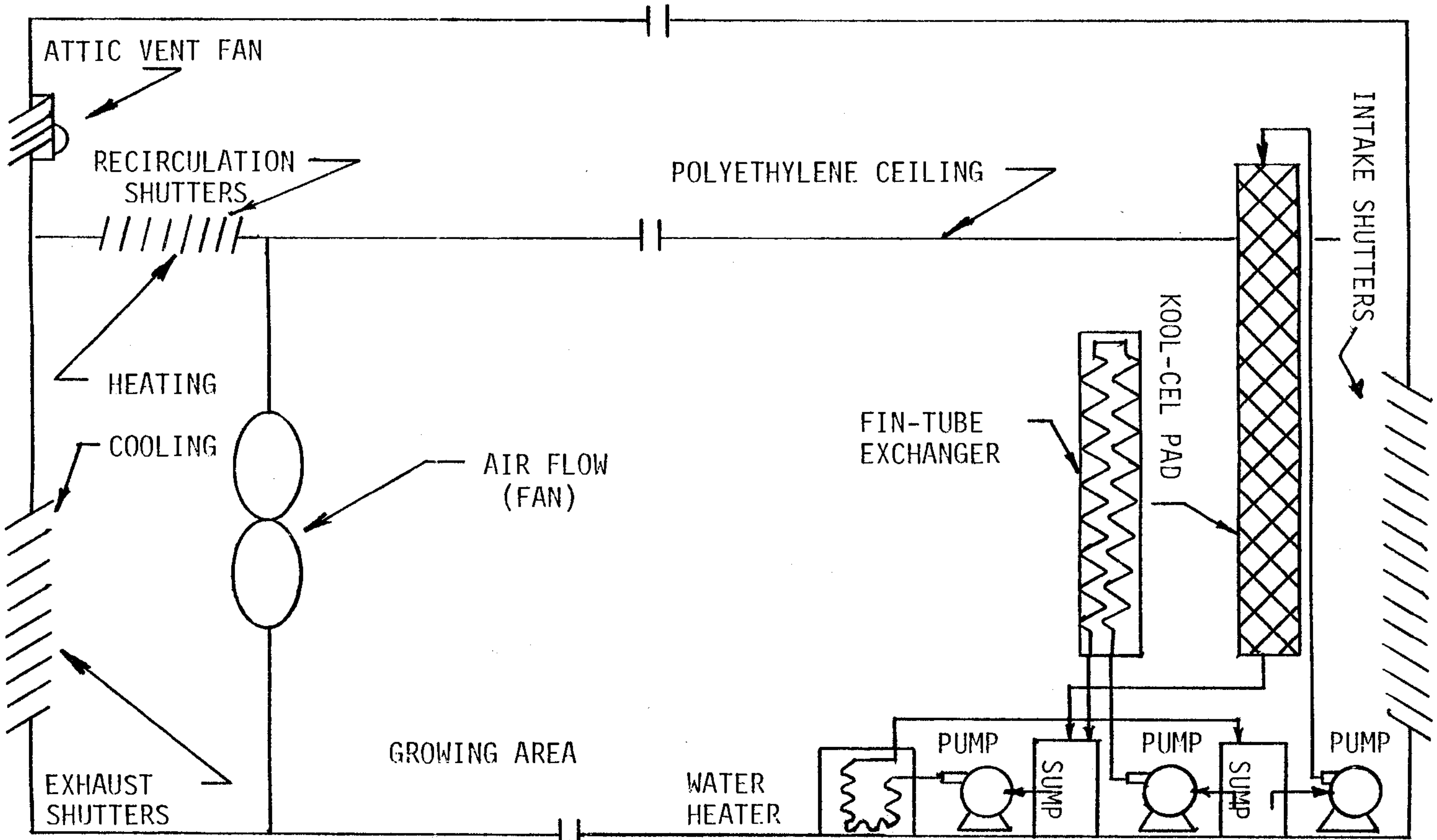

Figure 1. A schematic representation of the waste heat research greenhouse.

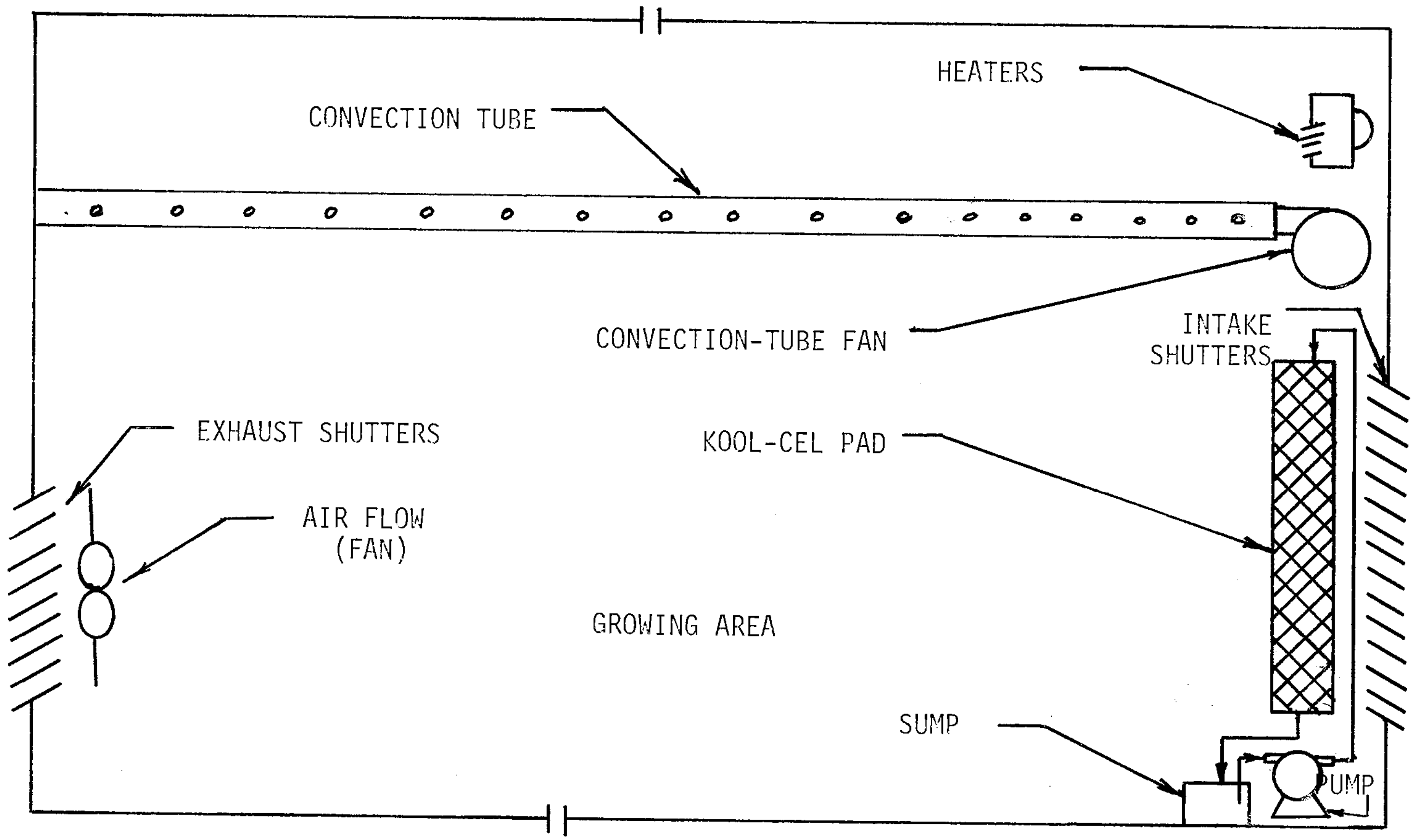

Figure 2. A schematic representation of the conventional greenhouse.

SECTION 2

CONCLUSIONS

HORTICULTURAL

Cultivars of the following bedding plant species were transplanted in late January and in early February of 1979 in the conventional greenhouse and in the waste heat greenhouse: begonia, browallia, coleus, geranuim, impatiens, marigold, pansy, petunia, salvia, tomato, and verbena.

The data included in this report suggest that the growth rate of the bedding plant species grown in this study are not adversely affected by the waste heat greenhouse environment.

With the exception of browallia and coleus, the survival rate for all other species of bedding plants grown in the waste heat research greenhouse was comparable to the survival rate of those species grown in the conventional greenhouse.

It was found that the plants grown in the conventional greenhouse flowered approximately 7.6 days earlier than those grown in the waste heat research greenhouse. However, this may be insignificant when considering the amount of money saved in fuel cost.

The following species of foliage plants were transplanted in each greenhouse from June 12, 1979, through July 14, 1979: *Ardisia humilis*, *Asparagus meyerii*, Begonia Caribbean mix, *Dizyotheca elegantissima*, *Hypoestes sanguinolenta*, *Philodendron pertussum*, *Schefflera compacta*, and *Syngonum podophyllum*.

All of the above species grown in the waste heat research greenhouse, with the exception of *Ardisia humilis*, showed a better growth rate than those grown in the conventional greenhouse. The growth of *Syngonium podophyllum* (nephthytis green) and *Philodendron pertussum* was statistically significantly better in the waste heat research greenhouse than in the conventional greenhouse.

The waste heat research greenhouse environment seems to be highly suited for growing foliage plants. This is probably brought about by the higher percent relative humidity in the waste heat research greenhouse than in the conventional greenhouse. Most foliage plants grow better under a high percent relative humidity.

In regards to survival rate, there were no statistically significant differences in survival rate between any of the species grown in the conventional greenhouse and the waste heat research greenhouse. No diseases were found in either greenhouse.

ECONOMIC

Because data were analyzed from only one crop of bedding plants and one crop of foliage plants, the economic conclusions made herein are of a preliminary nature.

This study revealed that the waste heat greenhouse equipped with a backup heating system would initially cost $84,506 to $90,605/.4 hectare (1 acre) or $208,730 to $233,794/hectare more to construct than the same size conventional greenhouse.

If waste heat can be supplied for $0.96/Gj ($1.02/MBtu) as compared to $3.04/Gj ($3.20/MBtu) and $6.45/Gj ($6.80/MBtu) for natural gas and No. 2 fuel oil, respectively, it may result in a savings of $13,520/.4 hectare (1 acre) or $33,394/hectare when compared to natural gas and $35,685/.4 hectare (1 acre) or $88,142/hectare when compared to No. 2 fuel oil.

Considering the current increasing price rates for natural gas and No. 2 fuel oil, the number of years required to break even for the cost of using waste heat to heat a greenhouse can probably be reduced to 3 to 4 years relative to heating with natural gas and 1 to 2 years for heating with No. 2 fuel oil by 1985.

With reference to marketing and consumer acceptance, customers did not show any preference in buying plants grown in the conventional greenhouse over those grown in the waste heat research greenhouse. The quality of plants grown in the waste heat research greenhouse was equal to the quality of those grown in the conventional greenhouse.

ENGINEERING

The engineering performance of the waste heat research greenhouse was compared with the conventional greenhouse in regards to heating, cooling and relative humidity.

In regards to maintaining heat, the waste heat research greenhouse was able to maintain an average low nighttime temperature of 12.0°C (53.6°F) over a 24-day period during the month of February while using water heated to 21.8°C (71.2°F) with a flow rate of 109 liters/minute (24 gallons/minute). The average low outside temperature for the same period was 2.6°C (36.7°F). Bedding plants grown in the waste heat research greenhouse did not suffer any adverse effects when compared to those grown in the conventional greenhouse. The waste heat research greenhouse is quite capable of providing a suitable winter-time temperature for the species of bedding plants tested in this project.

With reference to cooling, over a 4-day period the waste heat research greenhouse in July was able to maintain an average high daytime temperature of 30.0°C (86.0°F) in comparison to 29.4°C (85°F) maintained by the conventional greenhouse. The temperature of the entering effluent water used to cool the waste heat research greenhouse during this period was 43.1°C (109.6°F). The average outside temperature for the same four-day period was 38.6°C (101.5°F). These data indicate that warm effluent water can be used effectively to cool greenhouses, provided that much of the heat associated with the effluent water can be dissipated from the greenhouse through an attic before reaching the growing area.

For the most part, the relative humidity averaged only a few percent higher in the waste heat research greenhouse than it did in the conventional greenhouse. At no time was there condensation of water vapor observed on the foliage of plants grown in the waste heat research greenhouse or the conventional greenhouse.

SECTION 3

RECOMMENDATIONS

It is recommended that:

(1) The industry associated with the production of thermal water (waste heat) and the greenhouse industry apply the findings of this project to help eliminate thermal pollution of our waterways while benefitting both industries.

(2) A longer study period (4 to 5 years) be given to the evaluation of the crops observed in this study to help verify the results stated herein.

(3) A longer study period (4 to 5 years) be given to further evaluate the greenhouse design and control of the greenhouse environment.

(4) Additional research be given to finding those species of bedding plants and foliage plants that are best suited to the environment of a waste heat greenhouse.

(5) The growth response of woody ornamentals be tested with waste heat.

(6) More research be given to the economic evaluation in comparing waste heat greenhouse crop production with that of conventional greenhouse crop production.

SECTION 4

HORTICULTURAL STUDIES

Horticultural studies began in January, 1979. All horticultural studies followed the time table listed below:

1. January through April of 1979, cultivars of the 10 leading ornamental bedding plant crops along with the 2 leading vegetable bedding plant crops were grown in each greenhouse.

2. May through September of 1979, cultivars of the leading species of foliage plants and plants adapted for hanging baskets were grown in each greenhouse.

The greenhouses were not completed in time to schedule a fall crop (August through December of 1978). Therefore, this report contains data collected on bedding plants grown in each greenhouse from January, 1979, through April, 1979, and foliage plants grown June, 1979, through September, 1979.

Both the conventional greenhouse and the waste heat research greenhouse were operated as a commercial-type enterprise, and all parts of the system were evaluated, both from the standpoint of mechanical operation and as a satisfactory structure for plant growth.

Bedding Plants

All bedding plants were grown from super seddings obtained from the Ball Seed Company of Chicago, Illinois. Jiffy Mix Plus served as the soil medium.

Seedlings for each species and cultivar were transplanted to cell paks (32/tray), with the exception of geraniums which were transplanted into 0.1m (4 in) standard pots. After transplanting, trays and pots for each species were equally divided, and half were placed into the conventional greenhouse and the other half placed in the waste heat research greenhouse.

Figure 3 depicts the arrangement of the bedding plant species in both greenhouses. The statistical design used for the analysis of variance was the randomized complete-block design (10). A 1.2m (4 ft) space was placed between each block (replication).

Dry Weights (the whole plant). Table 1 depicts the mean dry weight of the whole plant for all species, except peppers. (The pepper seedlings were lost in both greenhouses due to mice). The growth rate of geraniums, petunias, and verbenas in the conventional greenhouse was statistically greater as compared with the same species grown in the waste heat research greenhouse. Although begonias, browallias, coleus, impatiens, marigolds,

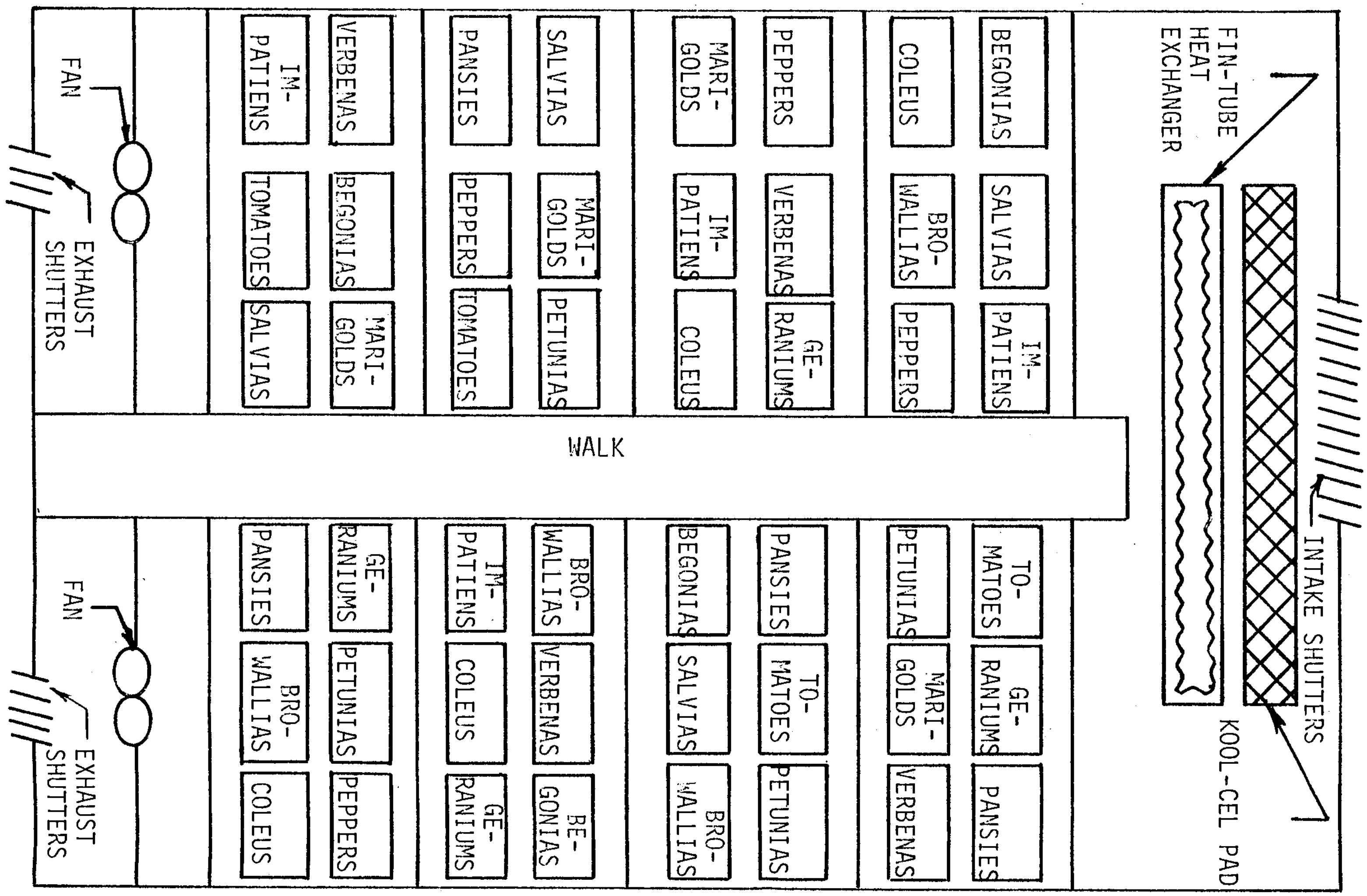

Figure 3. The arrangement of bedding plant species in the waste heat research greenhouse.

pansies, salvias and tomatoes grown in the conventional greenhouse showed a slightly better growth than those grown in the waste heat research greenhouse, the differences in growth rates were not statistically significant.

TABLE 1. MEAN DRY WEIGHT (g) of 8 WHOLE PLANTS/REPLICATION, APRIL 1, 1979[z]

SPECIES	DAYS FROM TRANSPLANTING	CONVENTIONAL GREENHOUSE	WASTE HEAT RESEARCH GREENHOUSE
Begonia	50	11.25a	10.87a
Browallia	48	8.00a	6.37a
Coleus	49	7.87a	6.25a
Geranium	47	17.25a	13.25b
Impatiens	49	12.87a	11.37a
Marigold	50	14.90a	14.00a
Pansy	40	11.50a	10.25a
Petunia	49	17.50a	14.87b
Salvia	48	13.00a	12.25a
Tomato	40	17.50a	15.30a
Verbena	40	13.70a	10.37b

[z]Means sharing uncommon letters are significant at the 5% level.

Table 2 shows the dates plants were treated with a 0.5% solution of B-nine, a growth retardant. The different species of bedding plants were sprayed with the growth retardant when they showed signs of stretching. B-nine was applied with a 7.57 l (2 gal) sprayer. Some difficulty was experienced with obtaining a uniform flow from the sprayer. This nonuniform application of B-nine probably resulted in some variation in growth rate noted among species grown in the same greenhouse as well as differences noted among species grown in separate greenhouses.

TABLE 2. SPRAY DATES OF B-NINE GROWTH RETARDANT

SPECIES	SPRAY DATES
Browallia	3-27-79
Coleus	3-13-79 & 4-16-79
Geranium	3-17-79, 3-27-79 & 4-16-79
Impatiens	3-12-79 & 3-27-79
Pansy	3-13-79
Petunia	3-12-79
Salvia	3-12-79
Verbena	3-12-79 & 3-27-79

Dry Weight (aerial plant parts). Table 3 shows the mean dry weight of the aerial parts of each species. Coleus and tomato plants grown in the conventional greenhouse showed a statistically significant better growth rate than those grown in the waste heat research greenhouse.

Petunias grown in the waste heat research greenhouse showed a growth rate significantly better than those grown in the conventional greenhouse, but better growth was probably due to a heavier application of B-nine in the conventional greenhouse.

TABLE 3. MEAN DRY WEIGHT (g) OF 20 AERIAL PLANT PARTS/REPLICATION, APRIL 12, 1979[z]

SPECIES	DAYS FROM TRANSPLANTING	CONVENTIONAL GREENHOUSE	WASTE HEAT RESEARCH GREENHOUSE
Begonia	61	19.75a	19.37a
Browallia	59	12.90	9.30a
Coleus	60	9.63a	6.63b
Geranium	58	40.87a	42.51a
Impatiens	60	31.00a	29.00a
Marigold	61	24.50a	25.50a
Pansy	51	22.12a	22.12a
Petunia	60	25.50a	37.75b
Salvia	59	22.37a	20.12a
Tomato	51	45.00a	42.50b
Verbena	51	23.50a	23.50a

[z]Means sharing uncommon letters are significant at the 5% level.

Geraniums and marigolds grown in the waste heat research greenhouse showed a slightly better growth rate (but not statistically) than those grown in the conventional greenhouse. The reverse was true for begonias, browallias, impatiens and salvias. Pansies and verbenas showed equal growth rates in both greenhouses.

Flowering Dates in Paks and Pots. Table 4 depicts and compares the number of days required to flower in paks and pots for each species in each greenhouse. The plants grown in the waste heat research greenhouse flowered on the average of 7.6 days (approximately one week) later than those grown in the conventional greenhouse. The greatest difference in flowering was noted in the geraniums which flowered 9 days earlier in the conventional greenhouse. Begonias, browallias, impatiens, and marigolds flowered 8 days earlier in the conventional greenhouse. Pansies, petunias, salvias, and verbenas grown in the conventional greenhouse flowered 7 days earlier than those grown in the waste heat research greenhouse.

Tomatoes are not listed in Table 4 because tomato bedding plants were sold according to plant size. Tomato plants had reached a saleable size in both greenhouses at the end of 4 weeks.

TABLE 4. FLOWERING DATES OF BEDDING PLANTS IN PAKS

SPECIES	CONVENTIONAL GREENHOUSE		WASTE HEAT RESEARCH GREENHOUSE		DAYS DIFFERENCE IN BLOOMING
	TIME FROM TRANSPLANTING TO BLOOM (DAYS)	DATE OF BLOOM	TIME FROM TRANSPLANTING TO BLOOM (DAYS)	DATE OF BLOOM	
Begonia	31	3-13-79	39	3-21-79	8
Browallia	61	4-12-79	69	4-20-79	8
Geranium	79	4-30-79	88	5-9-79	9
Impatiens	33	3-16-79	41	3-24-79	8
Marigold	23	3-5-79	31	3-13-79	8
Pansy	36	3-28-79	43	4-4-79	7
Petunia	39	3-21-79	46	3-28-79	7
Salvia	38	3-20-79	45	3-27-79	7
Verbena	45	4-6-79	52	4-13-79	7

Survival Rate. Table 5 shows the survival rate for each species of bedding plants in the conventional greenhouse and the waste heat research greenhouse. Only two species, browallia and coleus, showed a statistically significant better survival rate in the conventional greenhouse than in the waste heat research greenhouse. Browallia had an 81.0% survival rate in the conventional greenhouse and 66.0% in the waste heat research greenhouse. Coleus had an 89.5% survival rate in the conventional greenhouse compared to 78.0% in the waste heat research greenhouse. For all other species, the survival rate was not statistically significantly different between the two greenhouses.

TABLE 5. MEAN SURVIVAL RATE BASED ON 4 FLATS/REPLICATION (128 PLANTS), APRIL 10, 1979[z]

SPECIES	DAYS FROM TRANSPLANTING	CONVENTIONAL GREENHOUSE	WASTE HEAT RESEARCH GREENHOUSE
Begonia	59	95.5	91.7a
Browallia	57	81.0a	66.0b
Coleus	58	89.5a	78.0b
Geranium	56	98.8a	98.4a
Impatiens	57	100.0a	100.0a
Marigold	59	98.7a	96.7a
Pansy	49	99.2a	99.5a
Petunia	58	100.0a	100.0a
Salvia	57	96.2a	97.5a
Tomato	49	100.0a	100.0a
Verbena	49	97.5a	97.5a

[z]Means sharing uncommon letters are significant at the 5% level.

Foliage Plants

Foliage plants were grown in both greenhouses from June 12, 1979, through September, 1979. Table 6 shows the species and cultivars that were grown in both greenhouses.

TABLE 6. SPECIES AND CULTIVARS

SPECIES	TRANSPLANTING DATE
Ardisia humilis	7-14-79
Asparagus meyerii	7-14-79
Begonia Caribbean mix	6-21-79
Dizyotheca elegantissima	6-21-79
Hypoestes sanguinolenta	7-5-79
Philodendron pertussum	7-5-79
Schefflera compacta	7-5-79
Syngonium podophyllum	6-21-79

Foliage plants were also obtained from Ball Seed Company as super seedlings. All seedlings did not arrive on the same date, and transplanting took place from June 12, 1979, through July 14, 1979.

Dry weight (aerial plant parts). Dry weights were taken August 23, 1979, on *Dizyotheca elegantissima* (false aralia), *Ardisia humilis*, Begonia Caribbean mix, *Syngonium podophyllum* (nephthytis green) and *Hypoestes sanguinolenta* (polka dot plant).

For comparison, Table 7 depicts the mean dry weight for the five species of foliage plants grown in both greenhouses. With the exception of *Ardisia humilis*, the remaining species grew better in the waste heat research greenhouse than they did in the conventional greenhouse. *Syngonium podophyllum* (nephthytis green) grew significantly better in the waste heat research greenhouse than it did in the conventional greenhouse.

TABLE 7. MEAN DRY WEIGHT (g) OF AERIAL PLANT PARTS, AUGUST 23, 1979[z]

SPECIES	PLANTS/ REPLICATION	DAYS FROM TRANSPLANTING	CONVENTIONAL GREENHOUSE	WASTE HEAT RESEARCH GREENHOUSE
Dizyotheca elegantissima	10	63	6.38a	7.12a
Ardisia humilis	10	40	3.74a	3.66a
Begonia Carribbean mix	10	63	19.72a	21.43a
Syngonium podophyllum	20	63	34.80a	43.70b
Hypoestes sanguinolenta	20	63	100.20a	92.20a

[z]Means sharing uncommon letters are significant at the 5% level.

The mean dry weight for *Asparagus meyerii*, *Philodendron pertussum* and *Schefflera compacta* were taken on September 19, 1979. Table 8 shows that *Philodendron pertussum* grew significantly better in the waste heat research greenhouse than in the conventional greenhouse. Although the growth rates were not significantly better, both *Asparagus meyerii* and *Schefflera compacta* grew better in the waste heat research greenhouse than in the conventional greenhouse. These data indicate that foliage plants responded well to the waste heat greenhouse environment.

TABLE 8. MEAN DRY WEIGHT (g) OF AERIAL PLANT PARTS, SEPTEMBER 19, 1979[z]

SPECIES	PLANTS/ REPLICATION	DAYS FROM TRANSPLANTING	CONVENTIONAL GREENHOUSE	WASTE HEAT RESEARCH GREENHOUSE
Asparagus meyerii	10	67	5.31a	5.75a
Philodendron pertussum	5	76	19.32a	22.60b
Schefflera compacta	5	76	12.45a	13.96a

[z]Means sharing uncommon letters are significant at the 5% level.

Survival Rate. Table 9 shows the survival rate for each species grown in both greenhouses. In regards to survival rate, the waste heat research greenhouse provided a favorable environment equal to that of the conventional greenhouse. As a result of using normal disease preventive practices which were identical for each greenhouse, no evidence of any diseased plants was found.

TABLE 9. MEAN SURVIVABILITY BASED ON 100 PLANTS/REPLICATION, AUGUST 23, 1979[z]

SPECIES	DAYS FROM TRANSPLANTING	CONVENTIONAL GREENHOUSE	WASTE HEAT RESEARCH GREENHOUSE
Dizyotheca elegantissima	63	100.0a	100.0a
Ardisia humilis	40	100.0a	100.0a
Asparagus meyerii	40	100.0a	100.0a
Caribbean mix begonia	63	97.3a	96.8a
Syngonium podophyllum	63	100.0a	100.0a
Philodendron pertussum	49	100.0a	100.0a
Hypoestes sanguinolenta	49	100.0a	100.0a
Schefflera compacta	49	100.0a	100.0a

[z]Means sharing uncommon letters are significant at the 5% level.

SECTION 5

GREENHOUSE PERFORMANCE

Histories for temperature and percent relative humidity were compared for the conventional greenhouse and the waste heat research greenhouse. Temperature was recorded by a Bendix hygro-thermograph, and the percent relative humidity was measured with a hand psychrometer. Both temperature and the percent relative humidity readings were taken on the floor in the center of each greenhouse and on the outside of the greenhouses.

The flow rate of warm water was set at 109 l/min (24 gal/min) in the waste heat research greenhouse; the same flow rate was used for both winter and summer.

The temperature of power plant effluent water will vary according to whether the power plant is operating on a closed cycle or an open cycle and also according to each month of the year. Table 10 shows the temperature of effluent water for both a closed cycle and an open cycle power plant at the TVA's Browns Ferry nuclear power plant located in north Alabama. As shown in Table 10, the temperature of effluent water will be higher from a power plant operating on a closed cycle than from a power plant operating on an open cycle.

TABLE 10. AVERAGE MONTHLY TEMPERATURE OF EFFLUENT WATER AT BROWN'S FERRY NUCLEAR POWER PLANT LOCATED IN NORTH ALABAMA[a]

MONTH	OPEN CYCLE TEMPERATURE		CLOSED CYCLE TEMPERATURE	
	C	F	C	F
January	21.30	70.34	43.10	109.58
February	21.80	71.24	43.90	111.00
March	24.40	75.92	45.10	113.18
April	31.30	88.34	47.20	116.96
May	35.80	96.44	49.00	120.20
June	40.60	105.08	50.50	122.90
July	43.10	109.58	51.20	124.16
August	43.20	109.76	51.20	124.16
September	40.60	105.08	49.90	121.82
October	35.70	96.26	47.70	117.86
November	29.10	84.38	45.40	113.72
December	24.40	75.92	43.20	109.76

[a]Earl Burns. Personal Communication. TVA. October, 1978.

In this study, the temperature of water used in the waste heat research greenhouse simulated the temperature of effluent water coming from an open cycle power plant throughout the year, with the exception for short periods when the temperature of effluent water coming from a closed cycle plant was simulated for testing purposes only.

HEATING

During February, 1979, the temperature of effluent water from open cycle operation was 21.8°C (71.2°F) as shown in Table 10. The water used in the waste heat research greenhouse was heated to this temperature. Each greenhouse had the nighttime temperature set at 15.5°C (60°F) and a daytime temperature setting at 21.1°C (70°F).

During a 24-day period in February, the waste heat research greenhouse maintained an average low night temperature of 12.0°C (53.6°F). The conventional greenhouse average low night temperature was 14.1°C (57.4°F). This was a difference of 2.1°C (3.8°F). The average low outside night temperature for this period was 2.6°C (36.7°F) as depicted by Figure 4.

It is important to note here that the temperature control box in each greenhouse was located approximately 1.2 m (4 ft) above floor level. However, the hygro-thermographs recorded the temperatures at floor level where bedding plants are commonly grown in greenhouses. Temperature stratification is common in greenhouses and is the major reason for the difference between the greenhouse set temperature and the temperatures recorded at floor level.

Figure 5 depicts the average high daytime temperature maintained in the waste heat research greenhouse and the conventional greenhouse along with the average high outside temperature for the same 24-day period in February. The waste heat research greenhouse maintained an average high temperature of 18.4°C (65.1°F), whereas the conventional greenhouse maintained an average high temperature of 21.6°C (70.9°F). The average high outside temperature for the period was 12.6°C (54.7°F).

One of the coldest days of the year was February 18, 1979. On that date, there was an ice-snow storm. Wind speed reached above 17.9 m/s (40 mph) and the outside temperature reached a low of -4.4°C (24°F) (Figure 6). The lowest temperature reached in the waste heat research greenhouse was 8.9°C (48°F). This was less than 2°C difference in the lowest temperature recorded in the conventional greenhouse which was 10.6°C (51°F).

Figure 7 shows the 24-hour per day temperature histories for both greenhouses over a 4-day period in January.

The waste heat research greenhouse fin-tube heat exchanger system was designed to provide adequate dry heat. The fin-tube heat exchanger system consisted of 18 fin tubes, 0.05 m (2 in) diameter by 5.49 m (18 ft) length, 0.05 m (2 in) square plate fins, with 2 fins/0.03 m (1 in). However, the 1/3 hp pump provided only enough water to fill the bottom 4 fin tubes with warm water. Therefore, the heat in the waste research greenhouse was obtained by pumping water over the pad.

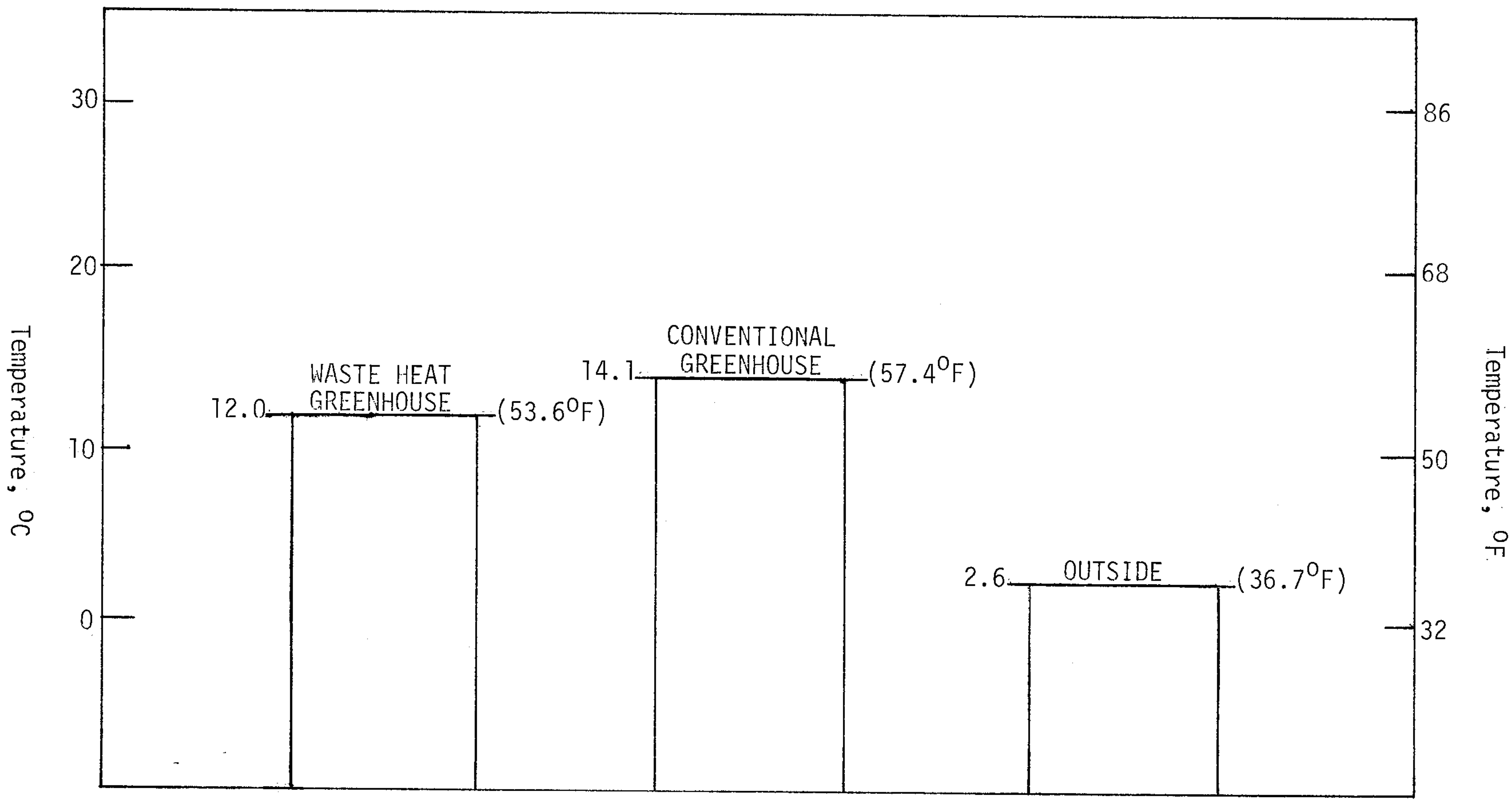

Figure 4. Average low night air temperature from February 1 through February 24, 1979.

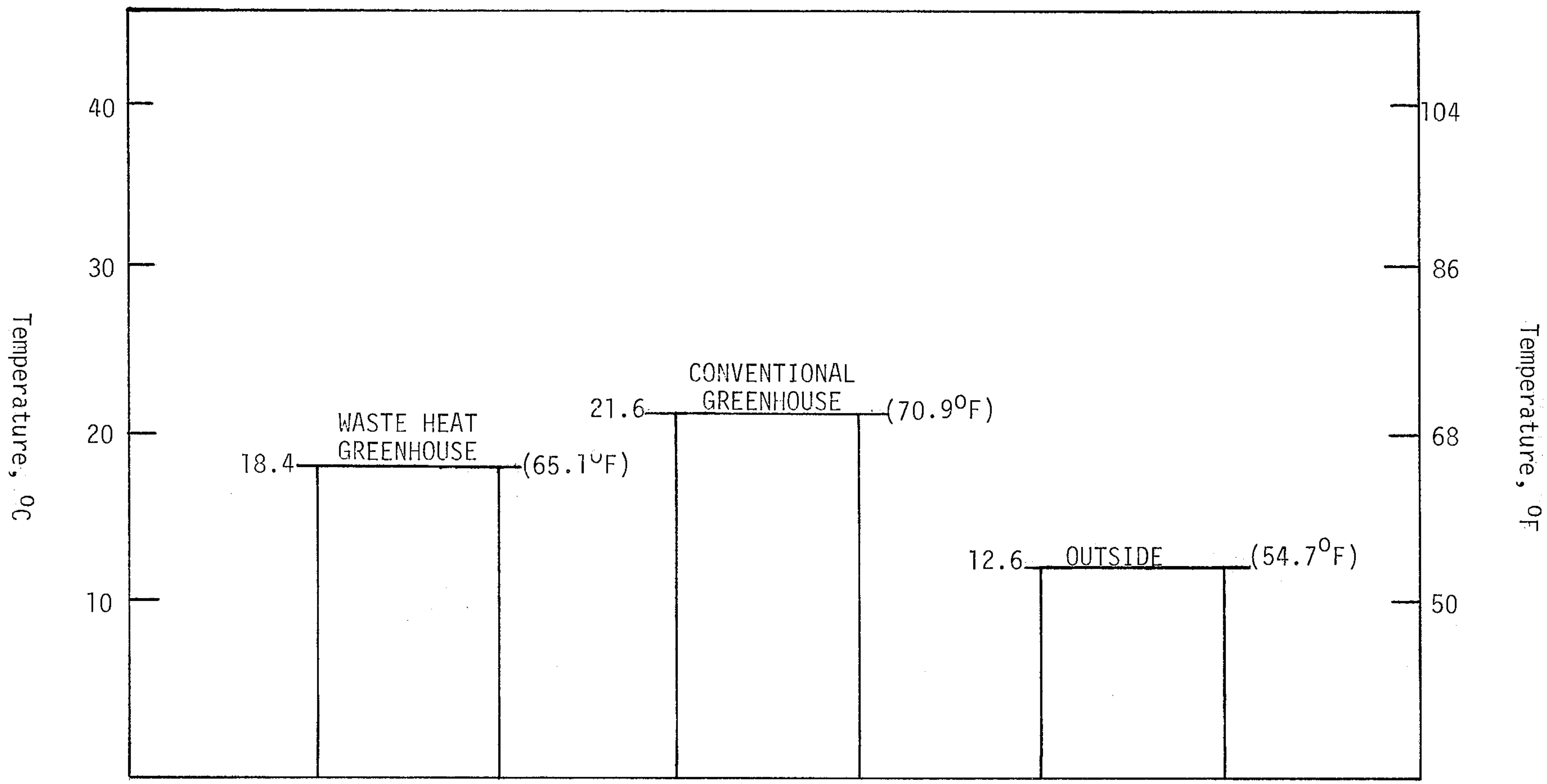

Figure 5. Average high daytime air temperature from February 1 through February 24, 1979.

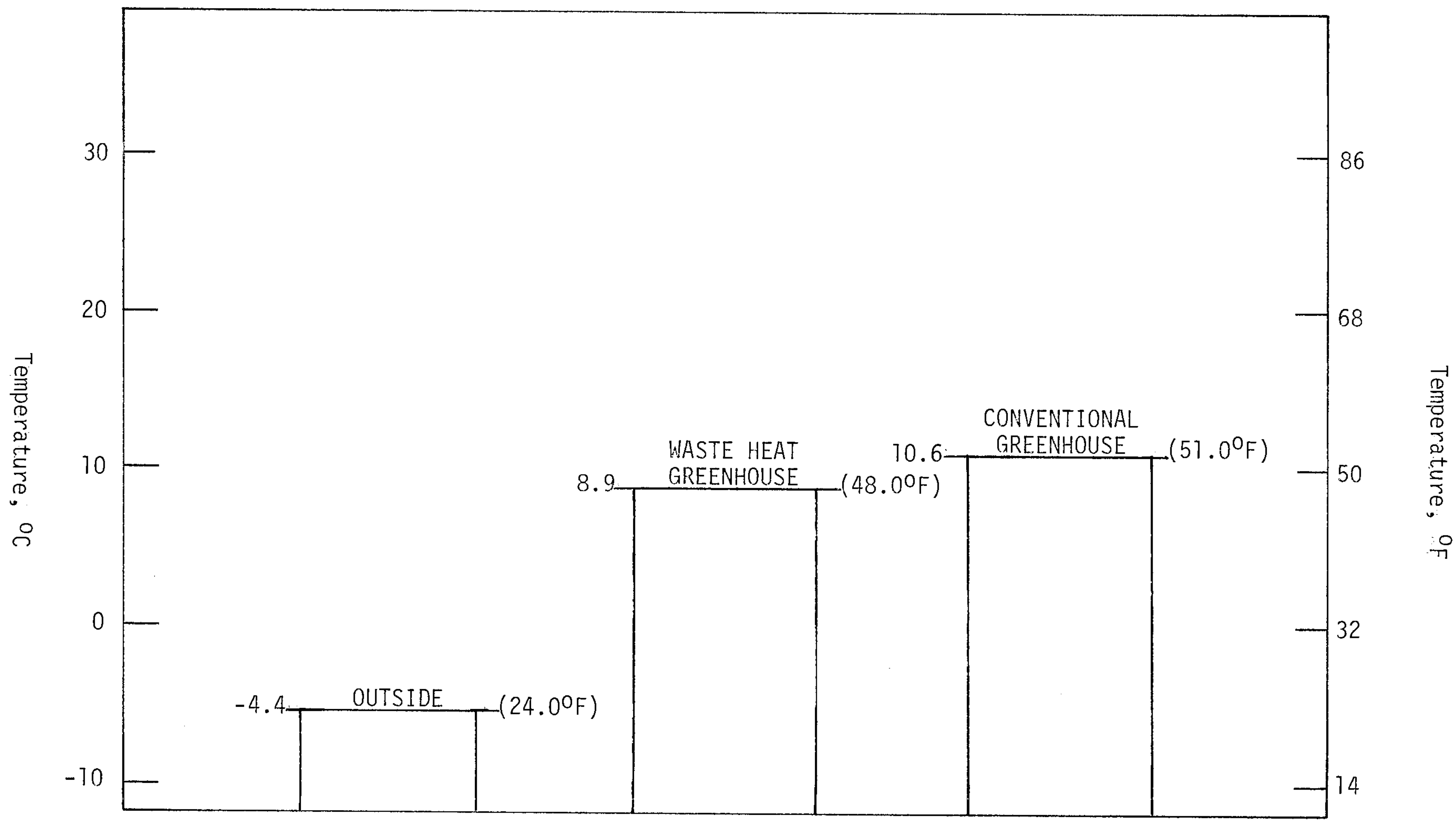

Figure 6. Comparative air temperature history of 24-hour period in the waste heat research greenhouse during an ice-snow storm on February 18, 1979.

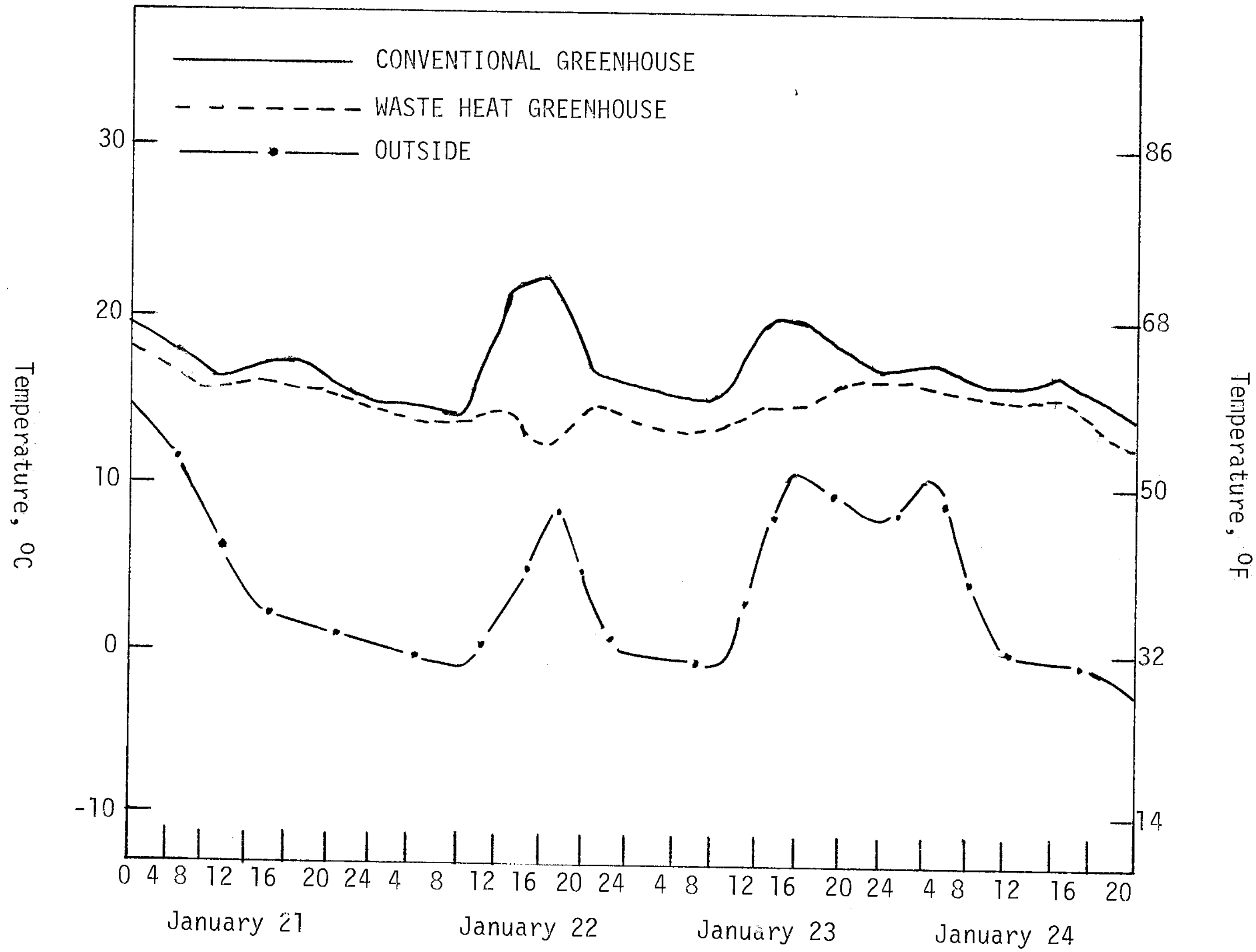

Figure 7. Comparative air temperature histories over a four-day period in January, 1979.

COOLING

Both greenhouses were covered with an 80 percent K-shade cloth to provide favorable light conditions for foliage plants and to aid in cooling. Figure 8 shows the average high temperature for both greenhouses during a hot 4-day period in July using warm water heated to 43.1°C (109.6°F) to cool the waste heat research greenhouse. During this 4-day period, the average high temperature in the waste heat research greenhouse was 30°C (86°F) and 29.4°C (85°F) in the conventional greenhouse. The average high outside temperature covering the same period was 38.6°C (101.5°F). Figure 9 shows cooling for 24 hours per day during the same 4-day period in July.

As mentioned previously, the temperature of effluent water coming from a closed cycle power plant is higher than the temperature of effluent water coming from an open cycle power plant. To test the effectiveness of cooling a greenhouse with the higher temperature effluent water coming from a closed cycle power plant and under high relative humidity conditions, the hot water heater was set at 51.2°C (124.2°F) for several days during July and August.

Figure 10 shows the temperatures maintained by each greenhouse and the outside temperature for a 4-day period during August while using the higher temperature water in the waste heat research greenhouse. The average high temperature reached in the waste heat research greenhouse during this 4-day period was 27.2°C (81°F) and 25.4°C (77.8°F) in the control greenhouse. This represented only a difference of 1.8°C (3.2°F) between the control greenhouse and the waste heat research greenhouse. The average high temperature reached outside of the greenhouses was 34.6°C (94.3°F) for the same 4-day period.

It is important to note that evaporative cooling is limited by the attainment of 100% relative humidity in a greenhouse and the relative humidity of the outside air supplied to the evaporative cooler. As mentioned in the next section, the relative humidity in the waste heat research greenhouse was generally higher than the relative humidity in the conventional greenhouse. However, the noted differences in relative humidity between the two greenhouses were generally small. Therefore, if the relative humidity can be controlled, the data represented by Figure 10 indicate that the higher temperature effluent water from a closed cycle power plant can be used effectively to cool greenhouses during the hot summer months.

An effort was made to determine the rate of sensible heat exchange from effluent water to air. The temperature of effluent water (from the hot water heater), the temperature of the effluent water 0.61 m (2 ft) below the top of the evaporative pad (attic level), and the temperature of the effluent water at the base of the evaporative pad 2.7m (9 ft) below the top of the evaporative pad, were taken. The average temperature of effluent water for each of the above points

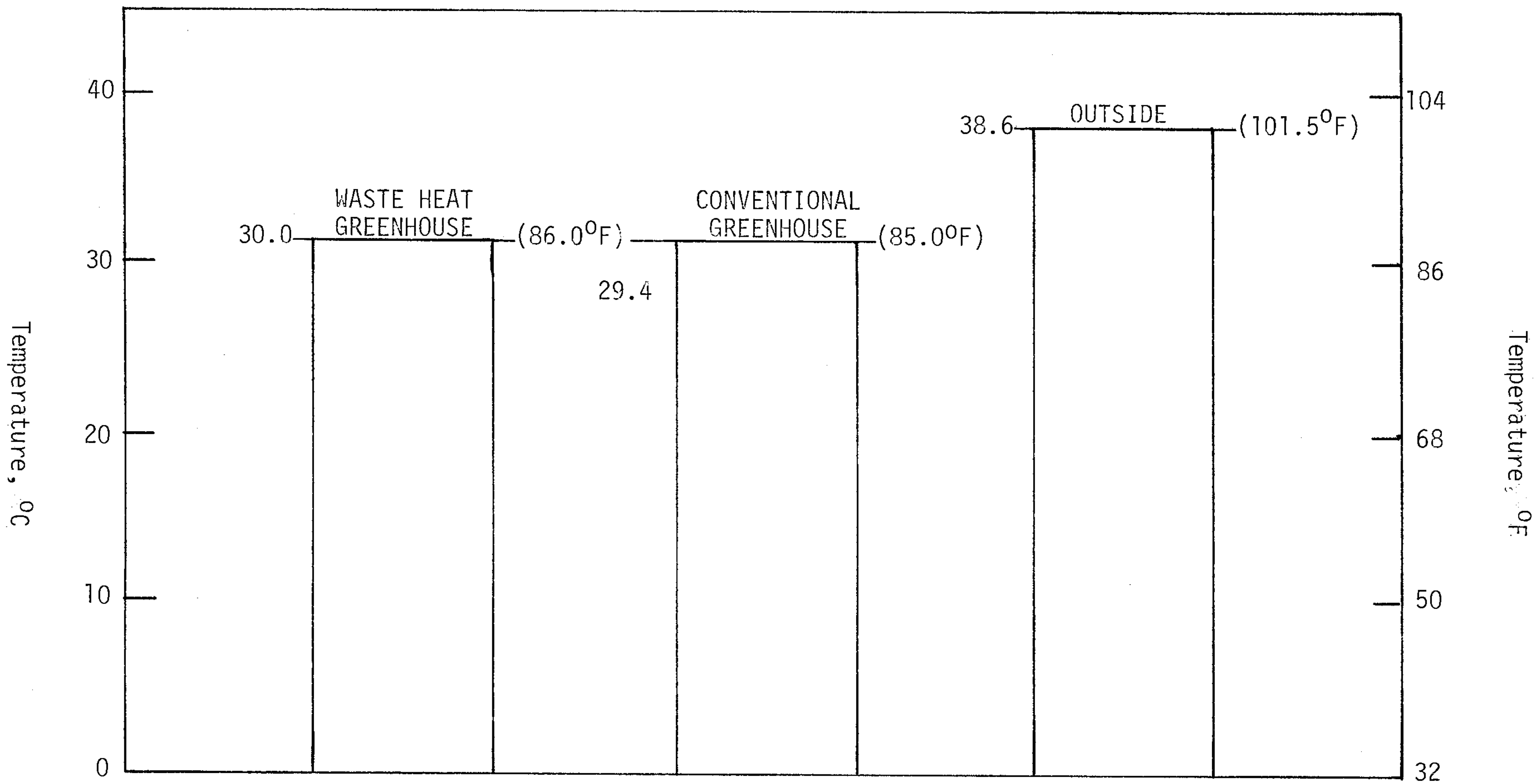

Figure 8. Average high greenhouse temperatures with water heated to 43.1°C (109.6°F) in the waste heat research greenhouse from July 1 through July 4, 1979.

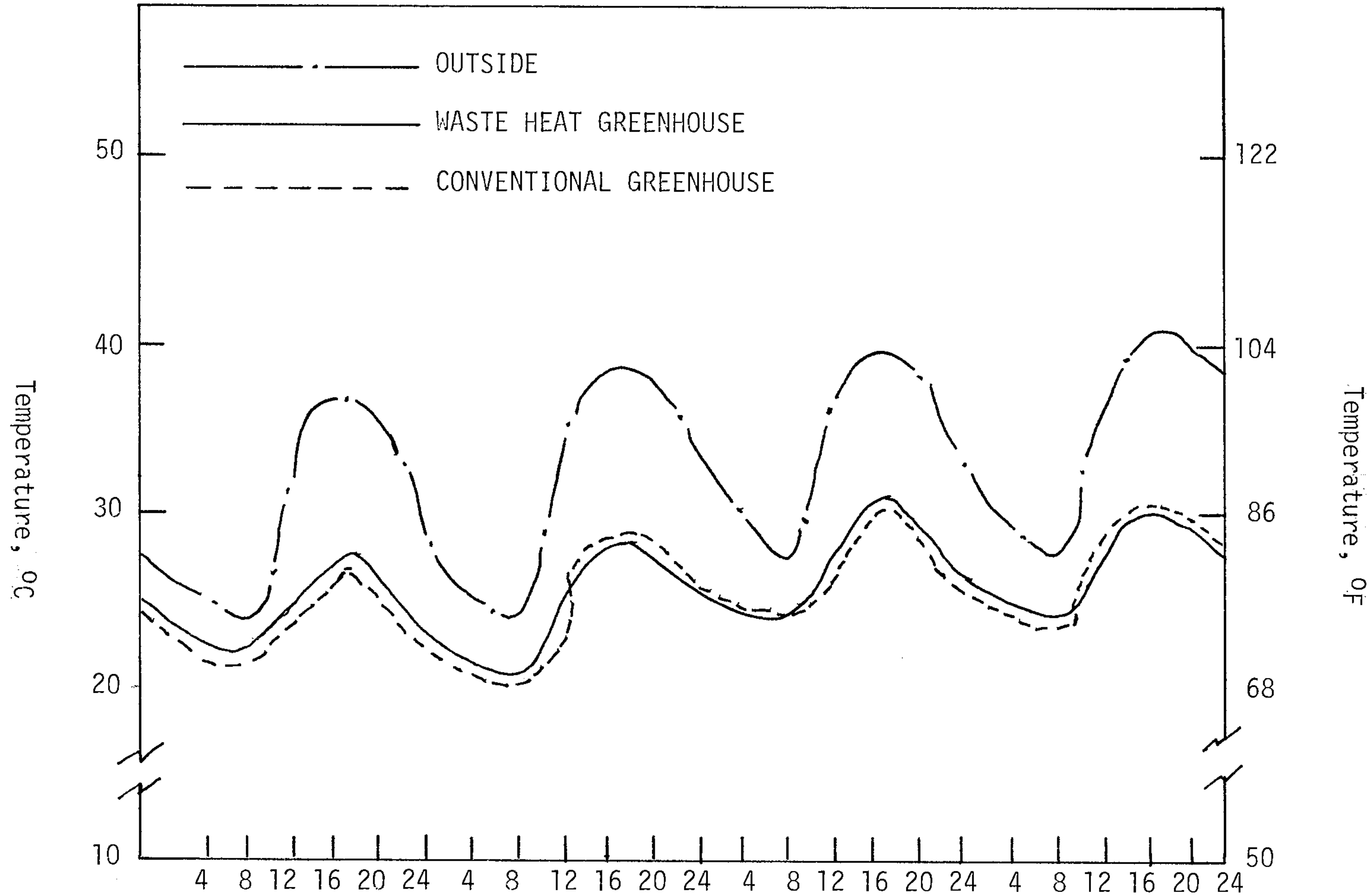

Figure 9. Comparative cooling during 24-hour cycles between waste heat greenhouse and conventional greenhouse using water heated to 43.1°C (109.6°F).

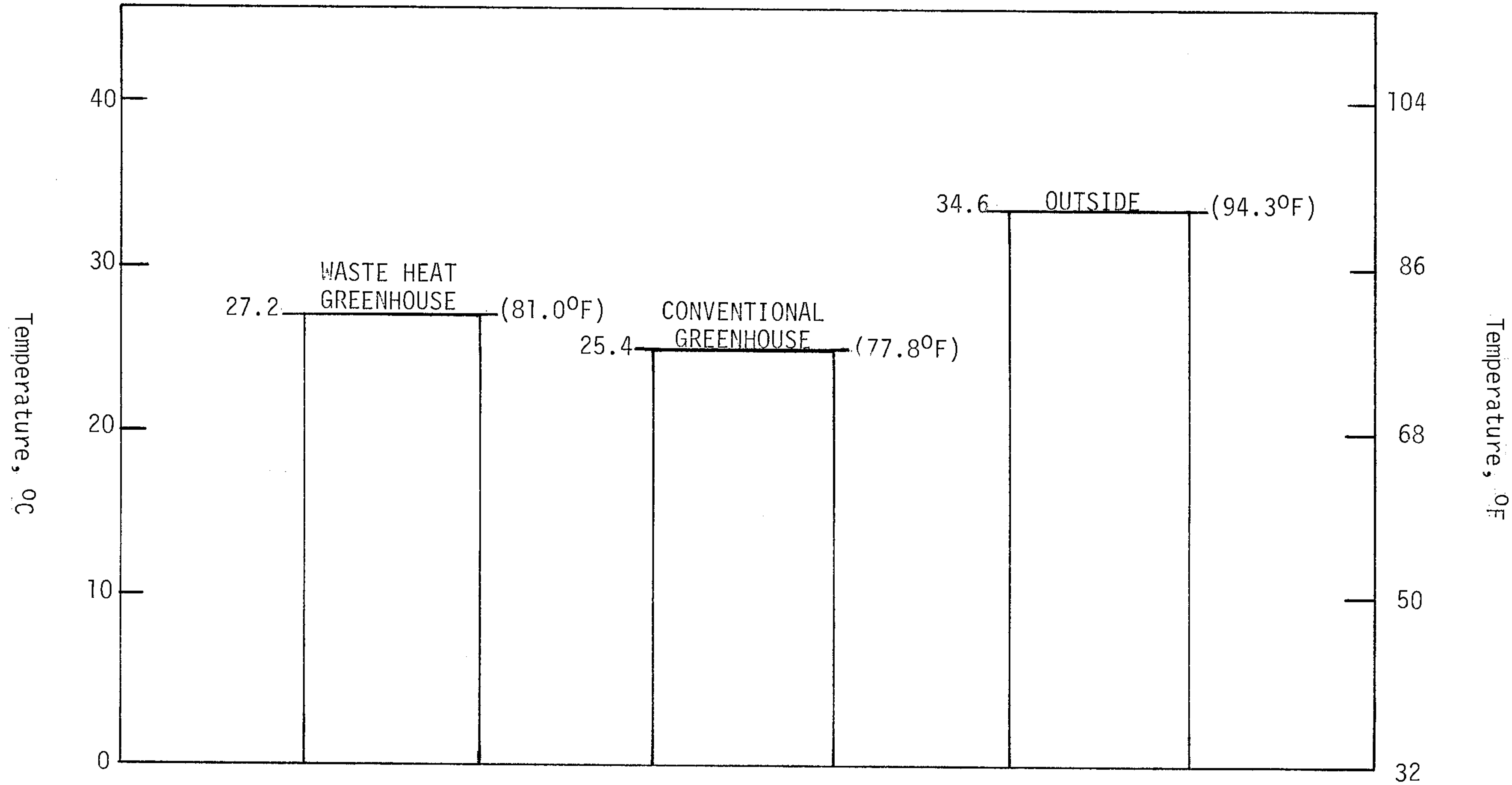

Figure 10. Average high temperatures reached in greenhouses using water heated to 51.2°C (124.6°F) in the waste heat research greenhouse simulating the temperature of effluent water from a closed cycle plant (August 14-17, 1979).

over a 6-day period (August 29, through September 3, 1979) is depicted in Figure 11. There is a total average drop in temperature of 27.5°C (49.5°F) from the temperature of the effluent water to the base of the evaporative pad and a 21.1°C (38.0°F) drop in temperature from the temperature of the effluent water just 0.61 m (2 ft) below the top of the evaporative pad. This indicated that 77 percent of the total amount of heat dissipated from effluent water by evaporative cooling occurred in the top 0.61 m (2 ft) of the evaporative pad. Since the top 0.61 m (2 ft) of the evaporative pad was above the attic level, it meant that over three-fourths of the heat from the warm effluent water was exhausted out of the attic plenum and never entered the growing area of the greenhouse. This also meant that the attic plenum was effective in dissipating the excess heat associated with effluent water from the growing area of the greenhouse during the warm months of the year. Furthermore, it permitted the use of a greater volume of warm effluent water during the warm months of the year without adversely affecting greenhouse crop production. The greater the volume of warm water used by a greenhouse operator during the summer months, the more beneficial it is to the power plant.

RELATIVE HUMIDITY

Due to the large cost over-run on the construction of the two greenhouses, funds were not available to purchase three recording hygrometers. A hand psychrometer was purchased during the spring of 1979. Therefore, data concerning the relative humidity were taken during the spring and summer months only.

All psychrometric readings were taken at floor level in the center of each greenhouse. Table 11 shows the relative humidity for each greenhouse and the outside for a 10-day period during the month of August under various environmental conditions and at different times during the 24-hour day. Table 11 shows that the relative humidity was generally higher in the waste heat research greenhouse than it was in the conventional greenhouse. However, in some instances there was either no difference or only small differences between the relative humidity in the waste heat research greenhouse and conventional greenhouse at the time the psychrometric readings were taken. At no time was there any observed condensation of water vapor on foliage of plants grown in either greenhouse. The high relative humidity did not pose a problem in either greenhouse.

It is important to note that each psychrometric reading in Table 11 took approximately 3 minutes. The psychrometric readings were made by using a slide rule humidity calculator. Although extreme care was used in taking the relative humidity readings from the slide rule humidity calculator, there is a possibility that some errors could have been made. This is probably exemplified by the 12:00 a.m. and 3:00 p.m. relative humidity readings taken on 8-23-79 for both greenhouses as well as for the relative humidity readings taken on 8-25-79 and 8-26-79 for the waste heat research greenhouse as depicted in Table 11. The relative humidity of the outside air and the prevailing

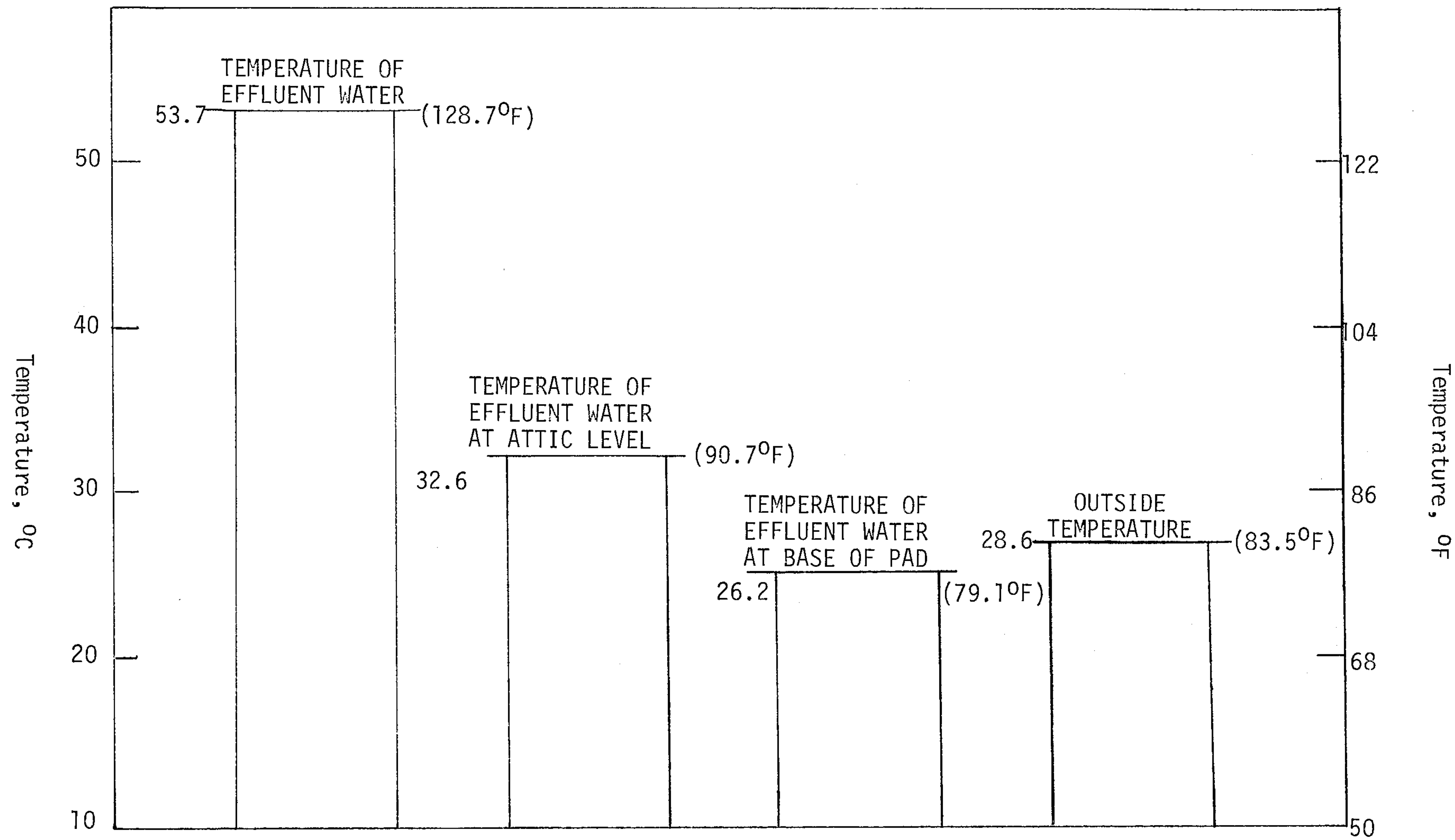

Figure 11. Potential for sensible heat exchange from effluent water to air during evaporative cooling in the waste heat research greenhouse from August 29 through September 3, 1979.

TABLE 11. PERCENT RELATIVE HUMIDITY WITH EFFLUENT WATER TEMPERATURE SET AT 51.7°C (125.0°F)

DATE	TIME	WASTE HEAT RESEARCH GREENHOUSE	CONVENTIONAL GREENHOUSE	OUTSIDE	OUTSIDE CONDITIONS
8-15-79	5:00 p.m.	80	80	62	cloudy
8-17-79	12:40 p.m.	83	82	68	cloudy
8-17-79	6:10 p.m.	92	87	68	cloudy
8-18-79	2:00 p.m.	70	70	52	partly cloudy
8-19-79	2:00 p.m.	68	65	46	clear-sunny
8-20-79	1:20 p.m.	80	80	56	partly cloudy
8-21-79	12:00 a.m.	92	92	80	midnight
8-22-79	12:00 a.m.	96	92	78	midnight
8-23-79	12:00 a.m.	96	98	100	midnight-raining
8-23-79	3:30 p.m.	96	92	100	raining
8-23-79	11:30 p.m.	100	100	100	night-raining
8-25-79	12:30 p.m.	80	72	78	partly cloudy
8-26-79	1:00 p.m.	82	70	72	partly cloudy
8-26-79	8:00 p.m.	96	96	84	cloudy

environmental conditions at the time the relative humidity readings were taken on the previously mentioned dates do not support the relative humidity readings found in the greenhouses and are probably erroneous.

The relative humidity in a greenhouse can quickly change as the external environmental conditions change (such as sunlight, cloud cover or rain). A better evaluation could have been given on the comparison between the relative humidity in the waste heat research greenhouse and the conventional greenhouse with a 24-hour per day recording hygrometer.

Although psychrometric determinations were not made during the winter months due to the lack of a psychrometer, visual observations were noted. When fogging was observed in the waste heat research greenhouse in the winter, it always occurred at night or during the daytime when the cloud cover was heavy. The fog always formed about 4 feet above the floor level and upward to the attic. The foliage of bedding plants, which were grown on the floor of each greenhouse, never showed any signs of condensation of water vapor.

Fog formation in the winter months can be eliminated from a waste heat greenhouse by the use of dry heat exchangers such as a fin-tube system. As noted earlier, the pump installed to circulate water through the 18 radiation fin-tubes has only sufficient capacity to circulate water through the bottom 4 of these tubes. Therefore, only 22 percent of the radiation fin-tube system was providing heat or participating in the heating and drying process.

SECTION 6

ECONOMIC APPROACH AND MARKETING STUDIES

ECONOMIC APPROACH

Because data were analyzed from only one crop of bedding plants and one crop of foliage plants, the economic projections made herein are of a preliminary nature.

The economic approach in this study is based on a comparison between a year-round commercial waste heat greenhouse operation with that of a conventional greenhouse operation. The projected savings in fossil fuel and cost of greenhouse production are on a .4 hectare (1 acre) basis.

The economics discussed in this study are based on one crop of bedding plants (winter and spring of 1979), one crop of foliage plants (spring and summer of 1979), and a projected crop of potted chrysanthemums and poinsettias (summer and fall of 1979). A cost return for each type of greenhouse operation is based on 0.093 m^2 (ft^2) of space used per flat base and per pot base for certain crops grown in this study with reference to an annual savings in fossil fuel and the cost of fossil energy for the greenhouse production of these crops.

The economic data in this study are based on the following: (1) the difference in construction cost of a .4 hectare (1 acre) waste heat greenhouse compared to a .4 hectare (1 acre) conventional greenhouse, (2) the cost of a back-up heating system for a .4 hectare (1 acre) waste heat greenhouse, (3) the average annual energy (Gj) requirement needed to heat a .4 hectare (1 acre) greenhouse in the U. S., (4) the current cost/Gj for natural gas and No. 2 fuel oil, (5) the projected cost for the waste heat, and (6) the wholesale value of certain crops grown in this study.

CONSTRUCTION COST

Basic Cost. The cost of construction materials used to build the 9.1 m X 21.9 m (30 ft X 72 ft or 2,160 ft^2) conventional greenhouse was \$5,264 or \$26.24/m^2 (\$2.44/ft^2). This cost is equivalent to \$106,157/.4 hectare (1 acre) or \$262,207/hectare. The cost of erecting the 201 m^2 (2,160 ft^2) conventional greenhouse was \$7.96/m^2 (\$0.74/ft^2) or \$1,600 which is equivalent to \$32,267/.4 hectare (1 acre) or \$79,698/hectare. The combined total cost of construction materials and the erection of the 201 m^2 (2,160 ft^2) conventional greenhouse was \$6,863 or \$34.19/m^2 (\$3.18/ft^2). This cost is equivalent to \$138,404/.4 hectare (1 acre) or \$341,858/hectare.

The cost of construction materials for the 9.1 m X 21.9 m (30 ft X 72 ft or 2,160 ft^2) waste heat research greenhouse was \$8,098 or

\$40.32/m^2 (\$3.75/ft^2). This cost is equivalent to \$163,310/.4 hectare (1 acre) or \$403,375/hectare. The cost of erecting the 201 m^2 (2,160 ft^2) waste heat research greenhouse was \$2,532 or \$12.58/m^2 (\$1.17/ft^2) which is equivalent to \$51,062/.4 hectare (1 acre) or \$126,123/hectare. The combined total cost of construction materials and erection of the 201 m^2 (2,160 ft^2) waste heat research greenhouse was \$10,630 or \$52.90/m^2 (\$4.92/ft^2). This cost is equivalent to \$214,372/.4 hectare (1 acre) or \$529,499/hectare.

The average cost of construction materials for the conventional greenhouse was \$26.24/m^2 (\$2.44/ft^2) compared to \$40.32/m^2 (\$3.75/ft) for the construction materials of the waste heat research greenhouse. This represents \$57,153/.4 hectare (1 acre) or \$141,168/hectare or 54 percent more for the cost of construction materials for the waste heat research greenhouse compared to the conventional greenhouse. This added cost for a waste heat greenhouse is primarily due to the added fin-tube heater system, attic fans, attic intake louvers, and attic exhaust shutters.

The erection cost for the conventional greenhouse was less than the erection cost for the waste heat research greenhouse by about 58 percent. The erection cost of the 201 m^2 (2,160 ft^2) conventional greenhouse was \$7.96/m^2 (\$0.74/ft^2) compared to \$12.58/m^2 (\$1.17/ft^2) for the same size waste heat research greenhouse. This represents an increase of \$18,795/.4 hectare (1 acre) or \$46,425/hectare or 58 percent more for the erection cost of a waste heat greenhouse compared to that of a conventional greenhouse. Like the difference in cost of construction materials, the added difference in the erection cost of a waste heat greenhouse is primarily due to installing the fin-tube heating system, the attic intake louvers, the attic exhaust fans, and attic exhaust shutters.

Although the waste heat research greenhouse used in this study did not have a back-up heating system, according to the analysis of data, it cost \$34.19 m^2 (\$3.18/ft^2) to construct a conventional greenhouse as compared to \$52.90/m^2 (\$4.92/ft^2) for a waste heat greenhouse; this means that the basic waste heat greenhouse will cost approximately 55 percent more to construct than a conventional greenhouse. Thus, the basic waste heat greenhouse will cost \$187,641/hectare or \$75,968/.4 hectare (1 acre) more to construct than will the conventional greenhouse (Table 12).

Back-Up Heating System. Since the waste heat research greenhouse used in this study does not have a back-up heating system, such a heating system was not used in computing the previous cost. However, a commercial waste heat greenhouse operator would need a back-up heating system in the event the power plant could not deliver warm effluent water to the greenhouse. The cost of a back-up heating system having the equivalent capacity of 4.5 Gj/hr/.4 hectare (4.3 MBtu/hr/acre) will cost approximately \$15,000 for oil and \$8,500 for natural gas (Table 13). This represents an additional \$3.66/m^2 (\$0.34/ft^2) for the oil-fired back-up heating system or \$2.15/m^2 (\$0.20/ft^2) for a gas-fired back-up system. This additional cost should be added to the previous \$52.90/m^2

TABLE 12. COMPARATIVE CONSTRUCTION COST BETWEEN THE CONVENTIONAL GREENHOUSE AND THE WASTE HEAT RESEARCH GREENHOUSE WITHOUT BACK-UP HEATING SYSTEM

	Conventional Greenhouse 9.1m X 21.9m (30 ft X 72 ft)	Waste Heat Research Greenhouse 9.1m X 21.9m (30 ft X 72 ft)	Difference
Cost of Materials:	$ 5,264.00	$ 8,098.00	$ 2,834.00
per square meter	26.24	40.32	14.08
per square foot	2.44	3.75	1.31
per .4 hectare	106,157.00	163,310.00	57,153.00
per hectare	262,207.00	403,375.00	141,168.00
Erection Cost:	$ 1,600.00	$ 2,532.00	$ 932.00
per square meter	7.96	12.58	4.62
per square foot	0.74	1.17	0.43
per .4 hectare	32,267.00	51,062.00	18,795.00
per hectare	79,698.00	126,123.00	46,425.00
Combined Cost:	$ 6,863.00	$ 10,630.00	$ 3,767.00
per square meter	34.19	52.90	18.71
per square foot	3.18	4.92	1.74
per .4 hectare	138,404.00	214,372.00	75,968.00
per hectare	341,858.00	529,499.00	187,641.00

TABLE 13. PROJECTED COST OF BACK-UP HEATING SYSTEM WITH AN OUTPUT OF 4.5 Gj/HR/.4 HECTARE (4.3 MBTU/HR/ACRE)

	Conventional Greenhouse	Waste Heat Research Greenhouse
Natural Gas:	0.00	
per square meter	$0.00	$ 2.15
per square foot	0.00	0.20
per .4 hectare	0.00	8,500.00
per hectare	0.00	20,995.00
No. 2 Fuel Oil:		
per square meter	$0.00	$ 3.66
per square foot	0.00	0.34
per .4 hectare	0.00	15,000.00
per hectare	0.00	37,050.00

(\$4.92/ft^2) cost for a waste heat greenhouse. Adding the cost of a back-up heating system, the cost of constructing a waste heat greenhouse would range from \$55.15 to \$56.56/m^2 (\$5.12 to \$5.26/ft^2) (Table 14). This cost is equivalent to \$223,027 to \$229,126/.4 hectare (1 acre) or \$550,877 to \$565,941/hectare for the construction of a waste heat greenhouse compared to \$138,521/.4 hectare (1 acre) or \$342,147/hectare for a conventional greenhouse. The waste heat greenhouse would initially cost \$84,506 to \$90,605/.4 hectare (1 acre) or \$208,730 to \$223,794/hectare more to construct than the same size conventional greenhouse.

TABLE 14. A PROJECTED COMPARATIVE CONSTRUCTION COST BETWEEN A CONVENTIONAL GREENHOUSE AND A WASTE HEAT GREENHOUSE BASED ON .4 HECTARE (1 ACRE) BACK-UP HEATING SYSTEM

Conventional Greenhouse		Waste Heat Greenhouse Back-Up Heating System	
		Natural gas	No. 2 Fuel Oil
per square meter	\$ 34.19	\$ 55.05	\$ 56.56
per square foot	3.18	5.12	5.26
per .4 hectare	138,521.00	223,027.00	229,126.00
per hectare	342,147.00	550,877.00	565,941.00

Greenhouse Energy Requirements

The amount of energy required to maintain an adequate temperature for greenhouse crop production will vary with location, type of greenhouse, energy conservation measures, and crop but may range from 5.3 Tj to 7.8 Tj/.4 hectare (5 to 7.4 billion Btu/acre) with about 6.5 Tj/.4 hectare (6.2 billion Btu/acre) being average (2). The average annual energy requirement for .4 hectare (1 acre) in Fort Valley, Georgia, is about 5.2 Tj (5 billion Btu). As previously mentioned, the minimum greenhouse temperature may vary according to the crops grown; however, the above greenhouse energy requirements are based on maintaining a minimum temperature ranging from 12.8^{o}C to 15.6^{o}C (55^{o}F to 60^{o}F).

Current Cost for Energy

Cost for Fossil Fuel. Thirty to forty percent of the cost of greenhouse crop production is for energy and is increasing everyday. Most greenhouses are heated by natural gas; No. 2 fuel oil ranks second.

The cost to maintain adequate temperatures for greenhouse crop production will vary according to the kind of fuel used. For the Fort Valley, Georgia area, the average current cost/Gj for natural gas is \$3.04 (\$3.20/MBtu), whereas the present average cost/Gj using No. 2 fuel oil is \$6.45 (\$6.80/MBtu). Thus, the annual cost of fuel (6.5 Tj/.4 hectare or 6.2 billion Btu/acre) when supplied by natural gas is \$19,760/.4 hectare (1 acre) or \$48,807/hectare and \$41,925/.4 hectare (1 acre) or \$103,555/hectare when supplied by No. 2 fuel oil.

Projected Cost of Waste Heat. Although several suggestions have been made, presently, no general conclusions are possible for what waste heat should cost. One suggestion was made that waste heat should cost \$0.19/Gj (\$0.20/MBtu) (1). However, perhaps a more realistic cost should be based on the cost of retrofitting a power plant with a greenhouse heating capability and allocating the cost of retrofitting to the power plant or greenhouse operator, or both. Because each site is expected to have different constraints, the break even cost for greenhouse operation is likely to be site specific and dependent on the market for greenhouse crops as well as power plant variables.

The investment and operating cost will vary with different sites. However, the Sherco demonstration project near Minneapolis, Minnesota may serve as a model (3). For the Sherco demonstration project, the calculated cost to deliver the warm water 1,067 m (3,500 ft) to the demonstration greenhouse and return it to the cooling tower the same distance was about \$0.96/Gj (\$1.02/MBtu)/.4 hectare (1 acre) based on the projected installed pipeline cost of about \$600,000 for a pipeline flow rate of 442 l/s (7,000 gallons/minute). Also included in the above cost to deliver the warm water to the greenhouse are the pumping costs, \$270/year, chlorination for bacterial slime control estimated to be \$550/year and total operating cost estimated to be \$1,500/year/.4 hectare (1 acre) greenhouse.

Projected Savings By Using Waste Heat. The projected savings in cost of greenhouse crop production in this study is based on the cost of \$0.96/Gj (\$1.02/MBtu) for waste heat as obtained in the Sherco demonstration project (3). As previously mentioned, on an annual basis the average .4 hectare (1 acre) greenhouse in the U. S. uses 6.5 Tj (6.2 billion Btu)/.4 hectare (1 acre), calculated to be approximately \$19,760 or \$48,807/hectare when supplied by natural gas. This is equivalent to \$4.88/m^2 (\$0.454/ft^2). The same amount of energy supplied by No. 2 fuel oil has been calculated to be about \$41,925/.4 hectare (1 acre) or \$103,555/hectare. This is equivalent to \$10.34/m^2 (\$0.962/ft^2). If waste heat can be supplied for \$0.96/Gj (\$1.02/MBtu), the cost to maintain adequate temperature for greenhouse crop production would be \$6,240/.4 hectare (1 acre) or \$15,413/hectare. This is equivalent to \$1.54/m^2 (\$0.143/ft^2). This represents a savings of \$33,394/hectare of \$13,520/.4 hectare (1 acre) when compared to natural gas and \$88,142/hectare of \$35,685/.4 hectare (1 acre) when compared to No. 2 fuel oil.

Since this study revealed that a waste heat greenhouse would initially cost \$84,506 to \$90,605/.4 hectare (1 acre) more to construct than a conventional greenhouse the same size, the number of years required to break even is an important consideration in an economic analysis. Two important factors in determining the number of years required to break even in a waste heat greenhouse operation are the cost of delivered waste heat/Gj (MBtu) and the kinds of fossil fuel waste heat is used to replace.

The effect of the cost of delivered waste heat on the number of years required to break even is supported by the data in Table 15. In Table 15, two other hypothetical costs for waste heat are compared with the cost of

TABLE 15. ESTIMATED POTENTIAL ANNUAL SAVINGS IN ENERGY COST USING THREE PRICES FOR WASTE HEAT COMPARED TO NATURAL GAS AND NO. 2 FUEL OIL AND THE NUMBER OF YEARS REQUIRED TO BREAK EVEN

BASED ON THE AVERAGE ANNUAL GREENHOUSE USE OF 6.5 Tj (6.2 BILLION BTU)/.4 HECTARE (1 ACRE)						
COST OF WASTE HEAT/Gj	COST OF ENERGY/ Gj SUPPLIED BY NATURAL GAS	COST OF ENERGY/ Gj SUPPLIED BY NO. 2 FUEL OIL	SAVINGS OVER THE USE OF:		YEARS REQUIRED TO BREAK EVEN OVER THE USE OF[y]:	
			Natural Gas	No. 2 Fuel Oil	Natural Gas	No. 2 Fuel Oil
$0.96/Gj[z]	$3.04/Gj[x]	$6,45/Gj[w]	$2.08/Gj	$5.49/Gj		
$6,240	$19,760	$41,925	$13,520	$35,685	6.2	2.4
$1.50/Gj	$3.04/Gj	$6.45/Gj	$1.54/Gj	$4.95/Gj		
$9,750	$19,760	$41,925	$10,010	$32,175	8.4	2.6
$2.00/Gj	$3.04/Gj	$6.45/Gj	$1.04/Gj	$4.45/Gj		
$13,000	$19,760	$41,925	$6,760	$28,952	12.5	2.9

[y]It is estimated that a waste heat greenhouse will cost $84,506 to $90,605 more/ .4 hectare (1 acre) than a conventional greenhouse.
[z]The cost of waste heat/Gj is based on the Sherco demonstration project.
[x]The cost of natural gas/Gj is based on Fort Valley, Georgia's (1979) price.
[w]The cost of No. 2 fuel oil is based on Fort Valley, Georgia's (1979) price.

waste heat/Gj (MBtu) established by the Sherco demonstration project (3). Regardless of the kind of fossil fuel replaced by waste heat, there is an increase in the number of years required to break even as the cost of waste heat/Gj increases.

Since different fossil fuels vary in cost, it is obvious that the number of years required to break even in a waste heat greenhouse operation is greatly determined by the cost of the fuel replaced by waste heat. As illustrated by the data in Table 15, the cost/Gj of heat supplied by natural gas and No. 2 fuel oil is $3.04 and $6.45, respectively. With waste heat costing $0.96/Gj, it requires 6.2 years to break even compared to 2.4 years for No. 2 fuel oil for a .4 hectare (1 acre) waste heat greenhouse. Should the price of waste heat increase to $2.00/Gj, the number of years required to break even if waste heat is used to replace natural gas is increased to 12.5 years as compared to 2.9 years for No. 2 fuel oil.

It is important to note that inflationary fuel rates and increased fuel costs were neglected in computing the above number of years required to break even by using waste heat to replace natural gas and No. 2 fuel oil. Based on past trends, it is safe to expect inflationary fuel rates and increased fuel costs to continue and thereby reducing the number years required to break even by operating a waste heat greenhouse. Considering the current increasing costs of the two above fossil fuels, the number of years required to break even for the cost of retrofitting can probably be reduced to 3 to 4 years for heating by natural gas and 1 to 2 years for heating by No. 2 fuel oil by 1985.

MARKETING STUDIES

Bedding Plants. Marketing studies began on April 6, 1979, and continued throughout the bedding plant season. Bedding plants were sold directly from the greenhouses. Browallia, coleus, impatiens, marigolds, pansies, petunias, salvias, and verbenas were sold at a wholesale price of $4.00/32-plant flat.

Customers did not show preference in buying plants grown in the conventional greenhouse over those grown in the waste heat research greenhouse. The quality of bedding plants grown in the waste heat research greenhouse was equal to the quality of those grown in the conventional greenhouse.

Bedding plants are usually grown in flats. A .4 hectare (1 acre) greenhouse will provide the space for 21,840 flats, 0.56 m X 0.28 m (22 in X 11 in). Petunias and marigolds are popular bedding plant crops and were sold at $4.00/flat. This represents a gross return of $87,360 .4 hectare (1 acre) or $2.00/0.3 m^2 (/ft^2).

Foliage Plants. Foliage plant crops are grown and sold in many different pot sizes. However, this economic study is based on a 0.08 m (3 in) pot size. *Hypoestes sanguinolenta* (polka dot plant), Caribbean begonia mix, and Dizyotheca elegantissima (false Aralia) can be easily grown to a saleable size within 4 weeks and can serve easily as late spring or early summer crops. A .4 hectare (1 acre) greenhouse can provide enough space for 599,040 0.08 m (3 in) pots.

In this study, the above plants grown in 0.08 m (3 in) pots were sold locally to a supermarket at \$0.50/pot which was the wholesale price. If all 599,040 0.08 m (3 in) pots could be sold at \$0.50/pot, the gross return per .4 hectare (1 acre) greenhouse would be \$299,520 or \$6.88/ 0.09 m^2 (/ft^2).

Certain foliage crops will probably give the greatest economic return due to rapid crop turn over.

Potted Chrysanthemums and Poinsettias. Although experimental data were never collected for chrysanthemums and poinsettias during the fall of 1978 (because the greenhouses were not completed in time), they are commonly grown as fall greenhouse crops. The average wholesale prices in 1978/0.15 m (6 in) pot of chrysanthemums and poinsettias were \$2.17 and \$2.47, respectively (6). In this study, poinsettias are being used as the fall crop for economic evaluation.

Poinsettias are normally grown in 0.15 m (6 in) pots. It is customary to allow 0.09 m^2 (ft^2) for each poinsettias pot base. The estimated crop value is \$53,797/.4 hectare (1 acre) or \$1.24/0.09 m^2 (/ft^2).

Economic Incentive to Use Waste Heat. Based on the above annual crop rotation, the projected gross income for a greenhouse operator is \$440,677/ .4 hectare (1 acre) or \$10.11/0.09 m^2 (/ft^2). If waste heat can be bought at \$0.96/Gj (\$1.02/MBtu), a greenhouse operator can expect to save annually \$13,520/.4 hectare (1 acre) or \$33,394/hectare when compared to heating with natural gas and \$35,685/.4 hectare (1 acre) or \$88,142/hectare when compared to heating with No. 2 fuel oil. On a /0.09 m^2 (/ft^2) basis, the estimated savings are \$0.310/0.09 m^2 (/ft^2) when compared to heating with natural gas and \$0.819/0.09 m^2 (/ft^2) when compared to heating with No. 2 fuel oil.

The above economic evaluation, however, is based on the greenhouse operator selling all of the plants grown in a .4 hectare (1 acre) greenhouse and receiving top prices for each crop which is rarely the case. If a greenhouse operator is unable to sell all of the plants produced for top prices, the need to save on the cost of fuel becomes even more essential to a profitable operation. Admittedly, it takes slightly more electricity to operate a waste heat greenhouse than it does to operate a conventional greenhouse. This added cost for additional electricity which is required to operate the fans and back-up heating system in a waste heat greenhouse is not included in the previous economic analysis. However, with a saving in the cost of fuel ranging from \$13,520 to \$35,685/.4 hectare (1 acre) or \$33,394 to \$88,142/hectare along with the scarcity of fossil fuel, it appears that the utilization of waste heat in the greenhouse production of high cash valued ornamental crops can be economically feasible.

REFERENCES

1. Beall, S. E., Jr., and G. Samuels. The Use of Warm Water For Heating and Cooling Plant and Animal Enclosures. 1971. ORNL-TM-3381

2. Berry, James W., and Herman H. Miller. A Demonstration of Thermal Water Utilization in Agriculture. Environmental Protection Technology Series. EPA-660/2-74-011. April, 1974.

3. Boyd, L. L., G. C. Ashley, J. S. Hietala, R. V. Stanfield, and T. R. C. Tonkinson. A Demonstration of Beneficial Uses of Warm Water From Condensers of Electric Generating Plants. EPA-600/7-80-099, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1980. pp. 53.

4. Burns, Earl R., Robert S. Piles, and Carl E. Madewell. Waste Heat Use In Greenhouses. State of the Art, Waste Utilization for Agriculture and Aquaculture. TVA and EPRI. August, 1978. Section 3: pp. 1-58.

5. Census of Agriculture. USDA. 1974. pp. III 38-39.

6. Crop Reporting Board. Floriculture Crops: Production Area and Sales, 1977 and 1978, Intentions for 1979. Economics, Statistics, and Cooperative Service, USDA, Washington, D. C. March, 1975. pp. 2-27.

7. Jensen, Merle H. The Future of Energy-Sources, Ideas. In: Proceedings of the Tenth International Bedding Plant Conference, Bedding Plants, Inc., Denver, Colorado, 1977. pp. 214-238.

8. Madewell, C. E., L. D. King, Johnny Carter, J. B. Martin, and W. K. Furlong. Progress Report: Using Power Plant Discharge Water in Greenhouse Vegetable Production. Bull. Z-56. Tennessee Valley Authority, Muscles Shoals, AL. January, 1975.

9. Olszewski, M. and H. R. Bigelow. Analysis of Potential Implementation Level for Waste Heat Utilization in Nuclear Power Industry. ORNL, October, 1978. pp. 1-27.

10. Steel, Robert G. D., and James H. Torrie. Principles and Procedures of Statistics. McGraw-Hill Book Company, Inc., New York, 1960. pp. 132.