WASTE HEAT USE IN A CONTROLLED ENVIRONMENT GREENHOUSE

E. R. Burns, R. S. Pile, and C. E. Madewell
Tennessee Valley Authority
Muscle Shoals, Alabama U.S.A.

ABSTRACT

The Tennessee Valley Authority has operated a pilot-scale waste heat greenhouse at Muscle Shoals, Alabama, since 1973. A conventional 7.3 x 30.5 meter glass-glazed structure has been modified to accommodate an environmental control system designed to use low-temperature warm water. The system uses a direct-contact heat exchanger surface for both heating and cooling.

The environmental control system has been evaluated over a wide range of ambient conditions, water temperatures, and water and air flow rates to establish operating parameters and capabilities associated with the waste heat system. Primary horticultural emphasis has been on the selection of adapted vegetable cultivars and on developing cropping management practices compatible with the waste heat environment.

An estimated cost comparison between the waste heat system and a conventional system indicated higher initial capital investment requirements but an overall cost advantage for the waste heat system.

INTRODUCTION

The primary objectives of the TVA waste heat utilization program are to identify potential uses of the energy contained in power plant discharge water and to develop and demonstrate technology to use this energy in efficient agricultural and aquacultural systems. The low temperature of the water as it exits power plant condensers limits its usefulness in traditional heating systems.

Approximately 50 percent of the total energy input in a coal-fired electric generating plant is lost to the condenser cooling water as waste heat and 10 percent is lost from the stack. The remaining 40 percent of the energy input is the generated electricity. The overall efficiency of nuclear plants is less, about 35 percent for a light water reactor. Approximately 65 percent of the energy input is discharged in the condenser cooling water.

The temperature of water and quantities discharged vary with design and site characteristics. For example, the temperature of the discharge from a low temperature rise condenser is only 6° to 11° C (ΔT) above the intake water. For a once-through system with a ΔT of 8° C, about 0.038 m^3/s water is required for each megawatt (MW) of generating capacity.

For a once-through, high-temperature rise condenser, the ΔT is from 14° to 17° C and requires about 0.022 $m^3/s \cdot MW$. Condensers for systems including cooling towers have ΔT's in the order of 18° to 21° C. For a cooling tower system with a ΔT of 21° C, about 0.021 $m^3/s \cdot MW$ is required. In the TVA area, river temperatures vary from about 5° C during winter months to 29° C during the summer. Thus, condenser discharge temperatures from a once-through system with a low ΔT would vary from 10° C in cold weather to 38° C during the summer; whereas, the high ΔT condenser discharge would vary from about 18° to 46° C. Normally, both the entry and exit temperatures of water from a cooling tower system are more uniform and more desirable for beneficial uses.

Waste heat utilization technology in economical production systems must be developed and demonstrated before significant use of waste heat resources can be realized. Guidelines need to be established for interfacing these systems with power plants. A number of projects are underway by TVA to develop technologies to utilize waste heat. This report focuses on a system developed to control greenhouse environments. System components were tested, crop production was evaluated, and a cost comparison of the waste heat system with a conventional system was made.

DESCRIPTION OF FACILITY

The interior of a 7.3- x 30.5-meter aluminum-framed, glass-glazed greenhouse was modified to accommodate a waste heat environmental control system for pilot studies. Modifications of the greenhouse (figure 1) included installation of the following: (1) a bank of evaporative pads and associated water distribution system, (2) a fin-tube heat exchanger, (3) a fiberglass attic forming a recirculation plenum, (4) motorized shutters to allow recirculation or once-through air flow, (5) attic vent fans, (6) a temperature control and instrumentation system, and (7) a water boiler to provide simulated power plant cooling water.

Due to the low wintertime temperatures of cooling water from open mode power plants and low efficiencies of conventional heat exchangers with this temperature water, a direct-contact evaporative pad system was developed and evaluated as the primary heat exchanger.

Two evaporative pad materials, aspen pads and CELdek[1] have been evaluated as direct-contact heat exchangers. An aspen pad bank 7.3 m wide by 2.4 m high and approximately 5 cm thick was initially used as the heat exchange surface. Results of experiments reported by Furlong [1] indicated superior performance of CELdek over aspen pads in a bimodal heating and cooling application. In June the aspen pads were replaced with the CELdek pad 7.3 m wide, 1.2 m deep, and 30.5 cm thick.

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1. A cellulose paper impregnated with antirot salts, rigidifying saturants, and wetting agents formed in a cross-fluted arrangement with 403 m^2 of surface area per m^3. Manufactured by the Munters Corporation, Fort Myers, Florida.

The water for heating or cooling was distributed to the pad through a perforated 5 cm diameter PVC pipe discharging upward into an impingement cover made with half of a 15 cm diameter PVC pipe. After passing through the pad, the water was collected in a sump for recirculation through the water boiler or direct return to the pad system. Heating was accomplished by recirculating saturated or nearly saturated air through the evaporative pad over which warm water was flowing. The evaporative pad was also used for cooling, using either warm water at low flow rates or nonheated recirculated water.

A 6.1- by 2.1-m copper-tubed, aluminum-finned dry heat exchanger with an extended surface area of 409 m^2 and an overall heat transmission coefficient of 12.37 $W/m^2 \cdot {}^\circ C$ at design conditions was located downstream of the evaporative pad. The fin-tube heater could be used to supply some dry heat to lower the relative humidity in the growing area. The evaporative pad and fin-tube could be operated either in parallel or in series.

A 180-kW electric water boiler was used to simulate power plant cooling water for the system. Water temperature was set at the expected average monthly temperature for the Browns Ferry Nuclear Plant and varied from about 21° C in January to 43° C in August.

Growing area temperature was controlled by the amount of air recirculated through the house. The possible air flow modes were (1) once-through, (2) 25-percent, (3) 50-percent, (4) 75-percent, and (5) 100-percent recirculation. Two fan speeds were also available. Control was achieved by individually opening or closing each of four banks of louvers on the inlet, outlet, and recirculation flow paths. The louvers were opened with relay-actuated motors and closed with springs. Five thermistors in the greenhouse supplied temperature signals for the control system.

Two 1.1-kW, 2-speed exhaust fans were used for air movement within the greenhouse. Rated air flow rates for the fans were 8.5 m^3/s with fans at low speed and 17.0 m^3/s at high speeds. The fans were located in a recessed area at the rear of the structure to exhaust air when cooling or direct flows upward into the attic plenum to be recirculated when heating. Two thermostat-controlled attic vent fans were used to prevent excessive temperatures in the attic during periods of high solar radiation and no air recirculation.

Instrumentation for the greenhouse consisted of detectors for water flows, water and air temperatures, and humidity, plus appropriate read-out and recording equipment. Orifices were used to measure total, pad, and fin-tube water flows. Circular 24-hour charts were used for recording various flows. A visual indication of makeup flow was obtained from a small rotameter with a range of 1.9 to 22.7 l/min.

Visual indicators on the control panel indicated fan speed and louver position, which were also recorded on a strip chart. The TVA weather station at Muscle Shoals provided hourly summaries of wind speed and direction, dry bulb and dew point temperatures, barometric pressure, and solar and total radiant flux.

ENVIRONMENTAL CONTROL SYSTEM EVALUATIONS

Environmental control system components were evaluated in terms of their capabilities and operating parameters during both heating and cooling modes of operation. Results of engineering tests with the CELdek pad system are summarized in this paper. More complete descriptions of specific tests and results are included in progress reports on the waste heat greenhouse project [2, 3].

Air Flow Rates

Air flow rates within the greenhouse were measured with an Alnor velometer, Type 3002, No. 14335, at the exit of the evaporative pad material. The pad exit area of 8.6 m^2 was divided into 18 sections of equal area, and air flow rates were measured at each section for all possible combinations of fan speeds and shutter positions. The average air flow rates measured are shown in figure 2. With the air flow system operating with no recirculation, the measured air flow rate was 85 percent of the rated fan capacity at high speed and 98 percent with fans on low speed. Volume air change rate was 1.7 times per minute with full fan speed and full ventilation and 1.0 time per minute with slow fan speed and full ventilation.

Heating System Performance

The primary function of the environmental control system during the heating mode was to maintain the growing area temperature within the acceptable range for crop production with water temperatures corresponding to the predicted monthly average open mode condenser cooling water temperatures at the Browns Ferry Nuclear Plant.

Operating parameters were varied in both attended and unattended experiments. Seasonal condenser cooling water temperatures are essentially fixed for a given power plant, but simulated discharge temperatures in these tests were varied to better characterize system performance. During unattended tests, conditions were preset and data were recorded continuously.

During attended experiments, the greenhouse was allowed to stabilize under a given set of conditons. This usually required from 15 minutes to 1 hour.

The CELdek heating system was evaluated at water flow rates of 12.4 and 18.6 l/min per meter of pad width with water temperatures ranging from about 20° to 32° C. An attempt was made to conduct these tests under similar ambient conditions, and all heating data discussed were collected at night to eliminate the effect of solar radiation. Ambient temperature averaged -1° C and varied from +4° to -6° C. The capacity of the water boiler limited the warm water temperatures and flow rates evaluated.

The lowest water flow supplied enough heat to maintain an acceptable growing area temperature (14° C) using 20° C water and full air recirculation. Less air recirculation was required to maintain acceptable growing area temperatures using higher water temperatures and flow rates.

The lowest ambient temperature encountered during attended tests was -6° C. The pad water flow rate was 18 l/min·m. Greenhouse night temperatures were maintained at 16.7° and 18.9° C with respective water temperatures of 19.4° and 22.2° C.

The amount of energy transferred in the CELdek heating system was difficult to quantify. Both heat and mass transfer occurred from the warm water to the air, and temperature stratification occurring downstream of the evaporative pad made reliable air temperature measurement difficult. An effort was made to quantify the change in energy of the greenhouse air at various pad water temperatures as it passed through the evaporative pad system. The pad flow rate was maintained at 18.6 l/min·m, and the results are shown in figure 3. Energy transferred ranged from 105 kW with 20.0° C water to 172 kW with 29.7° C water. These results were obtained with ambient temperatures of -5.6° to +3.9° C with fans operating on high speed resulting in 100-percent air recirculation.

The effect of mass transfer is included in the upper line shown in figure 3. A significant relationship between the total amount of energy transferred to the air and the water temperature was found. The relative humidity within the greenhouse remained at saturation during all tests with 100-percent recirculation and with no solar radiation or fin-tube flow. Under these conditions, air heating is accomplished along the saturation line. Using a psychromatic chart, effects of heat and mass transfer were separated and the sensible heat transfer for the water flow rate of 18.6 l/min·m at various water temperatures was plotted (lower line in figure 3). After separating the effects of mass transfer, the heat transferred in the pad system exhibited less dependence on water temperature, and the correlation between the heat energy transferred and the water temperature used was not significant. However, mass transfer does have an effect on the greenhouse environment due to the energy released as condensation occurs throughout the greenhouse as saturated air is cooled.

The effect of air flow rates on greenhouse heating at various water flow rates and temperatures was determined. At pad water flow rates of 18.6 l/min·m or greater, water temperature $\geq$21° C, and with the air recirculation system on automatic operation, acceptable temperatures were maintained with fans either on slow speed or full speed. However, temperatures were more uniform with fans on full speed during periods of high heat loss and low water temperatures, indicating that the higher air flow rates would be desirable during these periods.

Experiments were conducted to determine the performance of the fin-tube heater using the lower temperature water and three water flow rates (30.3, 36.3, and 68.1 l/min). The tests were made at night with fans operating at slow speed. A sufficient pad water flow rate was maintained to ensure that the air leaving the evaporative pad and entering the fin-tube heater was saturated.

During nighttime operation, with 100-percent air recirculation and without the fin-tube heater in operation, the greenhouse air was saturated throughout the growing area; and during periods of low ambient conditions, the growing area was noticeably foggy. The lowest fin-tube water flow rate (30.3 l/min) and the lowest water temperature (21.7° C) evaluated provided sufficient dry heat to alleviate the foggy conditions.

A hand-held motorized psychrometer was used to measure relative humidity downstream of the fin-tube heater for the 36.3 and 68.1 l/min flow rates. Average nighttime relative humidity was reduced from saturation to 97 percent and 92 percent, respectively, using 21.7° and 27.2° C water at 36.3 l/min and 93 percent and 90 percent at 68.1 l/min.

Greenhouse temperatures and relative humidities during a typical 4-day heating period in December 1975 are shown in figure 4. Both low and high solar radiation were experienced during periods of low ambient temperatures. Temperatures and relative humidities shown are representative of greenhouse conditions during the heating mode. The evaporative pad flow rate was 170 l/min, fin-tube heater flow rate was 56 l/min, and the water temperature fluctuated from 21° to 24° C.

Cooling Evaluations - Warm Water

The cooling performance of the evaporative system was evaluated using warm water at the predicted summer temperatures for the Browns Ferry power plant discharge water. Cooling effectiveness was measured during August 1976 on clear days with the exhaust fans operating on high speed and with no air recirculation within the greenhouse. Pad flow rates of 6.2, 12.4, and 18.6 l/min·m were characterized with water temperatures ranging from ambient wet bulb temperatures to approximately 35° C. For each run set conditions were established, and the greenhouse operated for 30 minutes before temperature and relative humidity measurements were taken. Four portable Taylor hygrometers and a portable motorized psychrometer were used to measure air temperatures and relative humidities.

Water temperatures evaluated were again limited by the output of the boiler providing the warm water. Ambient temperature, solar radiation, and wet bulb depression were different for each run; but an attempt was made to conduct the experiment on days with similar ambient conditions, and trends shown should be valid.

Ambient conditions, greenhouse temperatures, and cooling efficiencies achieved are shown in table 1. The cooling effect, measured as the decrease in air temperature divided by the ambient wet bulb depression, is expressed in percent. As could be expected, the cooling effect decreased as water temperature and flow rate increased. The poorest cooling performance measured, 58 percent, occurred at a water flow rate of 12.4 l/min·m with 32.3° C water; but the entering air immediately downstream of the pads was cooled to an average temperature of 23.3° C, while the average greenhouse temperature was 25.3° C, an acceptable temperature for plant growth. For all flow rates and water temperatures evaluated, the water exiting the pad was cooled to near the ambient wet bulb temperature.

Cooling Evaluations - Recirculated Water

If cooling the power plant discharge water during the summer months were not one of the objectives of the greenhouse, more efficient greenhouse cooling could be obtained by recirculating water over the evaporative pads in a closed system. The cooling process then becomes one of adiabatic saturation; that is, the temperature of the recirculated water approaches the wet bulb temperature of the incoming air, and the water is not cooled further. Evaporation occurs as unsaturated air is pulled across the pad. Energy from the incoming air supplies the latent heat of vaporization for the water that is evaporated, and the dry bulb temperature is lowered corresponding to the amount of heat expended in this evaporation.

Cooling efficiencies were determined for various water flow rates over a range of ambient conditions. In all cases, water flow rate was set and the greenhouse operated for several days. Data were collected on clear days when the ambient conditions dictated high fan speed and once-through air flow. The greenhouse control day temperature set point was 26.7° C for all experiments in an attempt to maintain optimum growing temperatures for cucumbers.

Data were analyzed and efficiencies determined during periods when the solar load was greater than 473 W/m^2, and the incoming wet bulb depression varied from 2.2° to 8.9° C. The cooling efficiencies measured at flow rates of 12.4, 18.6, 22.4, 26.1, and 29.8 l/min·m and corresponding ambient wet bulb depressions are shown in table 2. All wet and dry bulb temperatures used in calculating efficiencies were averages for one hour. Numbers in parentheses indicate the number of measurements obtained at the indicated ambient wet bulb depression and flow rates.

Regression analyses indicated a significant relationship between the cooling effect and the ambient wet bulb depression, both for each flow rate and for all flow rates combined. Regression equations for the different flow rates were not significantly different.

The average cooling efficiency for all conditions tested was 86.1 percent, which was adequate to maintain acceptable greenhouse temperatures. The lowest water flow rate evaluated, 12.4 l/min·m, was sufficient to keep the pad surface visibly wetted.

Following manufacturer recommendations, the cooling efficiency should have been approximately 91 percent at a water flow rate of 18.6 l/min·m with the high fan speed air velocity of 1.7 m/s through the evaporative pad material.

The effect of fan speed on the amount of cooling in the pad system and on the increase in air temperature through the greenhouse was also determined. Greenhouse temperatures were measured with recirculated pad water flow rates of 12.4, 18.6, and 24.8 l/min·m with the two different fan speeds available. Ambient conditions were similar for each run. The average cooling efficiency in the evaporative pad for all water flow rates was 74.0 percent with slow fan speed and 81.7 percent with full fan speed. As the air passed through the greenhouse, an average temperature increase of 4.2° C was measured for the slow fan speed and 3.3° C for full fan speed. The lower cooling efficiency and the greater increase in temperature through the greenhouse associated with the slow fan speed resulted in an average exit temperature 0.2° C higher than ambient conditions. With maximum fan speed, the exiting greenhouse air temperature was an average of 2.3° C lower than ambient temperature.

Figure 5 depicts greenhouse temperatures and relative humidities during a typical 6-day cooling period in July 1975 and illustrates typical conditions at various locations within the greenhouse during cooling with recirculated water and high solar loads. Data were collected immediately downstream of the evaporative pad ("N") and at the exit of the growing area ("S"). The fin-tube heater was not used during this period, and air flow rates were dictated by the control system.

HORTICULTURAL EVALUATIONS

Experiments were designed to study growth responses, measure yields, and identify and solve problems associated with production of tomatoes and cucumbers in the humid waste heat greenhouse environment.

Procedure

The experimental growing area consisted of six troughs constructed on a 1/2-percent slope from 1.9-cm plywood and lined with 6-mil polyethylene. Three troughs on the west side of the greenhouse were 0.6 by 18.3 m, and those on the east side 0.6 by 21.3 m. Aisles between troughs were 0.5 m wide except for the center aisle, which was 1.2 m to accommodate personnel, equipment, and visitors. Bottoms of the troughs were lined with 5 cm of pea gravel, and a slotted 3.8-cm diameter PVC pipe was placed in the center of the troughs lengthwise to ensure proper drainage of excess water and nutrient solution. Twenty cm of washed river sand was placed on top of the pea gravel for the growing medium. Nutrient solution was distributed via twin-wall irrigation tubing. The sand culture system and nutrient solutions used were based on systems described by Jensen [4, 5, 6], which have been used successfully in Arizona and other areas.

Cucumber Trials--Two cucumber crops were grown from February 3, 1975, to August 21, 1975. The Femfrance cultivar was selected. Two-week-old seedlings for the spring crop were transplanted into the sand beds on February 2, 1975, at a density of 0.67 m^2/plant, equal to about 14,800 plants/ha. This crop was terminated April 28, 1975. The summer crop was transplanted June 10, 1975, and terminated August 21. Cucumbers were pruned and trained according to the procedure reported by Bauerle [7].

Cucumber production was measured in five sections of the greenhouse to determine the degree of uniformity of production throughout the growing area. The control system was preset to maintain temperatures between 18° and 21° C at night and 27° to 30° C during the day using water at the predicted monthly discharge temperatures from Browns Ferry Nuclear Plant for heating. Tap water was used for cooling during the summer crop. Temperature and realtive humidity measurements were made at 0.5, 1.4, and 2.3 m elevations in the five sections.

Tomato Trials--Following the 1975 summer cucumber experiments, tomato trials were initiated. After cucumber plants were removed, sand beds were fumigated with Vapam at the rate of one liter/9.3 m^2. The environmental control system was preset to maintain the following established temperature conditions for optimum tomato production:

Light Conditions	Temperature (°C)
Bright days	24-26
Medium bright days	22-23
Dull days	20-22
Nights following bright or dull days	15-17
Nights following prolonged periods of dull days	14-16

The Tropic cultivar, which had performed best in previous tests in the waste heat environment [2], was selected for the fall 1975 crop. Four-week-old plants were transplanted into the growing area on September 8. Plants were set 61 cm apart in two rows 30 cm apart in each trough. This spacing gave approximately 0.36 m^2 of growing area per plant, equivalent to 27,400 plants per hectare.

Nutrient solution was applied once per day for the first week after transplanting and twice per day the next three days. The control system was then set to automatically irrigate with nutrient solution for five minutes three times per day, at 8 a.m., 12 noon, and 4 p.m. Chapin twin-wall irrigation tubing was used to distribute the nutrient solution. Tomato plants were tied, pruned, and pollinated according to recommended procedures [8].

Beginning the second week after transplanting, chlorthalonil (Bravo, Termil) was used at 7- to 14-day intervals to control diseases. Cultural practices to aid in disease control consisted of removing lower tomato leaves from the plants as the clusters matured to allow better air drainage throughout the greenhouse. Insecticides were applied as insect problems developed. The insecticide used was determined by the specific insect problem.

Insect	Insecticides Used
Spider mites	dimethoate (Cygon, Defend)
Aphids	malathion, diazinon, or Cygon
Whiteflies	Cygon, methomyl (Lannate, Nudrin), Vapona

The fin-tube heater was used when prolonged periods of cold, cloudy weather occurred to reduce relative humidity for effective pollination and to assist in disease control programs.

Temperature and relative humidity were recorded automatically at various locations in the greenhouse. Harvest operations were begun November 10 and continued until December 22.

Studies with tomatoes were continued in the spring of 1976 to evaluate tomato cultivars, planting densities, and cropping systems in an attempt to identify a system of tomato production compatible with the waste heat environment. These studies were conducted without using the fin-tube heater to determine if tomatoes could be produced in a humid waste heat greenhouse without the use of humidity reduction equipment.

Disease control was attempted by staying on a rigid fungicide spray schedule. Preventive applications of Bravo and benomyl (Benlate) were made at weekly intervals. Plants were monitored for disease symptoms during each pollination and pruning operation. As the incidence of disease increased, additional fungicide applications were made and plant foliage removed to improve air circulation. Insecticides listed previously were applied as needed to control insects.

The Tropic and Floradel tomato varieties were evaluated at two planting densities. Plants were set in rows 30 cm apart in troughs and spaced 46 or 61 cm apart within rows to give 0.36 and 0.26 m^2 per plant, respectively. This is equivalent to plant populations of 27,400 and 38,300 plants per hectare. Each plot was 1.5 m long and contained five and seven plants, respectively, for the two planting densities. Treatments were arranged in a randomized complete block design and replicated six times.

Another study was conducted to determine if removing the top portion of the tomato plants after the third cluster set fruit would allow high density planting and multiple cropping to increase annual production per square meter of greenhouse space. In this study, Tropic and Floradel were grown at 30.5- (0.18 m^2/plant) and 45.7-cm (0.26 m^2/plant) spacings within rows. Also included in the study were two semideterminate varieties--Homestead 24 and Bonnies NWR--at the 45.7-cm spacing. Two crops with these treatments were grown during the period January 23 to August 10, 1976. Yields were compared with those obtained from a conventional planting of Floradel and Tropic at the 45.7-cm spacing. These treatments were arranged in a randomized complete block design and replicated three times.

Five-week-old plants for these studies were transplanted on January 23, 1976. The plants for the second crop in the topping experiments were transplanted May 10. Tomato harvest was begun on April 7 and completed in all except the topping experiments July 23. The harvest period for the first crop in the topping experiments extended from April 7 to May 4. The second crop was harvested from July 12 to August 10.

Results and Discussion

Cucumber Trials--Some variation occurred in production of cucumbers in the test sections of the greenhouse with yields from the spring crop ranging from 6.5 to 7.4 kg/plant. Yields from the summer crop ranged from 5.3 kg to 6.2 kg/plant. Average yield from the two crops was 6.9 and 6.3 kg/plant, respectively. At the planting density of 14,800 plants/ha, these yields are equivalent to 102.1 and 93.2 tonnes per hectare.

The environmental control system using simulated power plant discharge water during the winter and spring and tap water in the summer kept the average greenhouse temperatures within the acceptable range for cucumber production. Horizontal temperature variations of 1.7° to 3.3° C occurred in the five sections monitored, and vertical differences from 1.1° to 2.8° C occurred in each section.

Daytime humidity measurements varied considerably among sections at all three elevations (68 to 98 percent), especially during periods of low sunshine as frequently occurred during this crop. However, from these limited data and observations during production, no correlation could be made between humidity levels in various sections with plant diseases and crop yields. These observations on European cucumbers confirm earlier results, showing them to be well adapted to the waste heat greenhouse environment.

Tomato Trials--During the fall and winter of 1975, the environmental control system utilizing simulated condenser cooling water maintained greenhouse temperatures within the optimum range for greenhouse tomato production throughout the growing period from mid-September to late December. The coldest ambient temperature (-10° C) during this crop occurred on December 19. Greenhouse temperatures at the monitoring stations ranged from 17° to 20° C. These temperature levels were achieved using warm water at 25° C at a flow rate of 170 l/min over the pad and 57 l/min through the fin-tube heat exchanger.

There was little variation in yield of tomatoes in different sections in the greenhouse. On the west side, yields ranged from 2.8 to 3.0 kg/plant and on the east side 2.8 to 3.1 kg/plant. The average yield per plant over the entire greenhouse was about 3.0 kg/plant.

A high incidence of plant disease occurred during the fall crop. Botrytis (Botrytis cinerea) outbreaks coincided with prolonged periods of low solar radiation. Weekly applications of Bravo-6F fungicide, removal of lower tomato leaves to improve air circulation, and the use of the fin-tube heater to lower humidity succeeded in bringing the disease under control.

The system continued to maintain optimum temperature levels for tomatoes during the winter, spring, and summer of 1976. Yield and size of tomatoes from the experiment evaluating planting density and cultivars are shown in table 3. There was no statistical difference in the yield of Floradel and Tropic cultivars among planting densities. There was a significant difference between the two densities. The low plant population averaged almost 8.6 kg of marketable fruit per plant as compared with 6.7 kg at the higher density. However, yield per unit area of greenhouse space was greater at the higher density planting, almost 257 t/ha as compared with 236 t/ha at the lower density. There was no significant reduction in size of marketable fruit by increasing the planting density. The Tropic cultivar produced larger No. 1 fruit than Floradel, averaging almost 226 g as compared with 183 g.

There were no production problems identified that were related to the high planting density. At both densities, vegetation lapped in the narrow aisles by the time of the first harvest. This complicated operations such as pollinating, pruning, spraying, and harvesting. Wider row spacings would have made these tasks easier and also would probably have improved air circulation. These preliminary results indicate that high density planting of tomatoes in the waste heat environment may be possible to increase annual production, but sufficient space is needed between rows to accommodate personnel for routine chores.

Results of the topping experiment are shown in table 4. Tropic and Floradel produced higher yields than the semideterminate varieties (Bonnies NWR and Homestead 24). Most plants of the semideterminate varieties had self-topped at the time Tropic and Floradel were topped, and many plants had four to five clusters. Floradel and Tropic plants topped after the third cluster produced fewer tomatoes per plant, but more tomatoes per hectare when grown at the high density planting (54,800 plants/hectare), indicating that high density planting of topped plants may be practical. However, the two crops of topped plants did not produce as many tomatoes as a single crop of the same varieties grown from January 22 to July 16, 1976, in an adjacent growing area.

Normally, yield and quality are better from the lower clusters of greenhouse-grown tomatoes. The effect of topping generally causes an increase in size of fruit. However, in this study, fruit-set on upper clusters was very good and quality was excellent; therefore, the advantages from topping were not as evident. Less labor for pruning, tying, and spraying was required by the topped plants. This offset the extra transplanting labor and expense of growing and setting new plants. The primary advantage of the topped plants was that disease control was less difficult. The shorter plants were easier to cover with fungicide sprays and allowed better air circulation. The main disadvantage of a topping system is the long period of vegetative growth required for each crop for such a short harvest period. Such a system might have potential in a waste heat environment if plantings in a commercial facility could be staggered so that a constant supply of fruit could be made available to a market or timed so the harvest periods would coincide with high demand periods.

Experiments conducted in the waste heat greenhouse during the spring of 1976 showed that under the conditions experienced, good yields of tomatoes may be produced in the humid waste heat environment without using a fin-tube heater or other equipment to reduce the relative humidity, provided special attention is given to disease prevention and control. Preventive fungicide applications were made on a weekly basis, and plants were closely monitored for symptoms of disease outbreak. During prolonged periods of low solar radiation, botrytis outbreaks occurred even though weekly spray applications of Bravo were being made. The most severe outbreak during the spring crop occurred during early May. The disease caused a yield reduction because a number of young fruit aborted. The disease outbreak was arrested by increasing the frequency of fungicide application to once every five days for three applications and using a combination of Bravo and Benlate. In addition, lower leaves and excess plant foliage were removed to improve air circulation.

Although good yields were achieved without humidity reduction equipment, additional studies are being conducted to determine if disease control can be achieved under more adverse ambient conditions.

COST ADVANTAGE OF THE WASTE HEAT SYSTEM

A 1974 survey of the vegetable greenhouse industry in the seven Valley States [9] indicated that the industry was growing. At that time, there were 561 growers operating 1,492 houses. Since 1974, the rate of expansion of the greenhouse industry has decreased. One of the major problems facing the future development of the Valley greenhouse industry is high heating cost. The waste heat greenhouse system appears to offer an opportunity to help reduce cost. A comparison between the initial capital cost requirements for components of a waste heat system and a conventional system is shown in table 5. The comparison was made assuming that the power plant discharge water is made available at the greenhouse site.

For a 223 m^2 greenhouse, the initial capital investment would be about $6,388 higher for the waste heat system. Much of this extra cost is associated with the recirculation attic, exhaust fans, and shutter system. Changes to reduce cost, such as eliminating the attic and recirculating air through an adjacent parallel greenhouse, are planned for a commercial-scale greenhouse to be constructed at the Browns Ferry Nuclear Plant.

Table 6 indicates the annual cost advantage for the waste heat greenhouse system. The importance of the cost of fuel for the conventional house is evident. Assuming that marketable crop yields and quality are not significantly different between the two systems, there is an annual cost advantage of $980. In addition, traditional fossil fuels are conserved. Projecting these savings to a hectare-size house shows an estimated waste heat system annual cost advantage of about $44,000 and conservation of over 823 m^3 of fuel even after adjustment is made for the extra electricity used by the waste heat system.

CONCLUSIONS

Results from these studies show that the environmental control system using simulated power plant discharge water can maintain adequate greenhouse temperatures for tomato and cucumber production. Components of the environmental control system, including CELdek as a direct contact heat exchange surface, performed adequately.

The high relative humidities associated with the system required special attention to plant disease. Effective disease control required a rigid fungicide spray program, good sanitation, and cultural practices to improve air circulation. Good production of tomatoes was achieved without the use of the fin-tube heater to reduce relative humidity levels during the spring of 1976. However, additional studies are needed over a wide range of ambient weather conditions before a conclusion is made regarding the necessity of the dry heat exchanger.

The cost comparison between the environmental control system of the waste heat greenhouse and a conventional system showed that although the initial capital investment requirements for the waste heat system were higher there was an overall annual cost advantage. Future advantages are anticipated to be even greater as fuel costs continue to rise.

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TABLE 1

AMBIENT CONDITIONS, GREENHOUSE TEMPERATURES, AND COOLING EFFICIENCIES

DURING SUMMER COOLING TESTS WITH WARMED WATER

USING FULL FAN SPEED AND ONCE-THROUGH COOLING

TVA WASTE HEAT GREENHOUSE, MUSCLE SHOALS, ALABAMA, 1976

Run	Pad Flow (l/min·m)	Water Temp. (°C)		Ambient		Greenhouse Temperatures (°C)[a]				Cooling Efficiency[b] (%)
		In	Out	Temp. (°C)	Wet Bulb Depression (°C)	N db	N wb	S db	S wb	
1	6.2	23.1	22.0	29.7	8.1	22.1	21.6	26.1	23.3	95
2	12.4	23.1	22.0	29.3	7.7	22.9	22.0	26.1	22.9	83
3	18.6	23.1	22.2	29.7	7.8	23.4	22.5	26.9	23.5	81
4	6.2	30.0	22.8	31.7	9.7	24.0	23.2	28.3	24.7	79
5	12.4	25.6	18.9	26.6	8.3	20.7	19.8	25.1	21.9	71
6	18.6	25.6	20.0	30.6	11.4	21.9	20.8	25.5	22.1	76
7	6.2	32.8	19.4	27.5	9.2	21.3	20.4	25.3	21.7	67
8	12.4	30.3	21.4	30.6	10.6	23.4	22.7	27.6	23.7	67
9	18.6	30.3	21.1	29.4	10.6	22.6	21.6	26.5	23.1	65
10	6.2	35.0	19.9	30.0	11.7	22.8	21.4	27.4	23.6	62
11	12.4	32.2	20.6	28.9	9.9	23.3	22.4	27.3	25.6	57

a. "N" or "S" denotes north or south end of greenhouse, "db" is dry bulb temperature, and "wb" is wet bulb temperature.

b. Cooling efficiency is normally used to express cooling effectiveness under adiabatic saturation conditions but is used here to indicate relative cooling effects.

TABLE 2

COOLING EFFICIENCIES MEASURED

AT VARIOUS FLOW RATES AND WET BULB DEPRESSIONS

TVA WASTE HEAT GREENHOUSE

MUSCLE SHOALS, ALABAMA, 1976

Ambient Wet Bulb Depression (°C)	Cooling Efficiency (%)				
	Q = 12.4[a]	Q = 18.6	Q = 22.4	Q = 26.1	Q = 29.8
8.9	-	-	-	-	91.0 (2)
8.3	100.0 (1)[b]	-	-	-	88.2 (4)
7.8	-	-	-	-	82.0 (1)
7.2	90.5 (2)	-	-	-	88.3 (3)
6.7	-	83.0 (1)	-	91.5 (2)	86.3 (3)
6.1	-	91.0 (1)	-	84.0 (2)	91.0 (2)
5.6	90.0 (2)	85.0 (2)	82.0 (2)	90.0 (4)	85.0 (3)
5.0	81.3 (3)	83.5 (2)	89.0 (3)	79.7 (3)	78.0 (2)
4.4	88.0 (1)	87.5 (2)	92.5 (4)	72.0 (2)	84.5 (2)
3.9	89.5 (2)	85.5 (2)	-	81.5 (2)	71.0 (1)
3.3	92.0 (1)	83.0 (1)	-	100.0 (1)	83.5 (2)
2.8	-	80.0 (1)	-	-	-
2.2	-	75.0 (1)	-	88.0 (1)	88.0 (1)
Average Efficiencies	88.7 (12)	84.2 (13)	89.0 (9)	85.0 (17)	85.7 (26)

a. Flow rates are in l/min·m.
b. Numbers in parentheses are the number of observations at the conditions indicated.

TABLE 3

MARKETABLE YIELD AND SIZE OF TROPIC AND

FLORADEL TOMATOES AT TWO PLANTING DENSITIES

IN THE TVA WASTE HEAT GREENHOUSE AT MUSCLE SHOALS, ALABAMA

JANUARY 22 - JULY 16, 1976

		Yield of Marketable Tomatoes[b]		Average Tomato Size (g)		
Variety	Planting Density[a]	Per Plant (kg)	Per Hectare (Tonnes)	No. 1	No. 2	Culls
Tropic	27,400	8.67 a	238 a	230 a	252	105
Floradel	27,400	8.53 a	234 a	181 b	266	88
Tropic	38,300	6.72 b	257 b	221 a	266	130
Floradel	38,300	6.72 b	257 b	184 b	249	82

a. 27,400 plants/ha = 0.36 m^2 per plant (45.7 cm in rows).
   38,300 plants/ha = 0.26 m^2 per plant (61.0 cm in rows).

b. Average of six replications. Means followed by the same letter are no different at the 5% level of probability.

TABLE 4

YIELD OF TOMATOES TOPPED AFTER THE THIRD CLUSTER

IN THE TVA WASTE HEAT GREENHOUSE AT MUSCLE SHOALS, ALABAMA

JANUARY 22 - AUGUST 10, 1976[a]

Cultivar	Density (plants/ha)	Yield of Marketable Tomatoes[b] kg/plant Crop 1	Crop 2	Total	t/ha Crop 1	Crop 2	Total
Floradel	54,800	2.3 b	2.3 b	4.6 b	113 a	127 a	240 a
Tropic	54,800	2.1 b	2.2 b	4.3 b	118 a	119 a	237 a
Floradel	38,300	2.6 a	2.6 a	5.3 a	102 a	101 b	204 b
Tropic	38,300	2.9 a	2.5 ab	5.4 a	111 a	94 bc	205 b
BNWR	38,300	2.4 ab	2.1 bc	4.5 bc	92 b	79 c	172 c
HS-24	38,300	1.6 b	1.8 c	3.4 c	51 c	68 c	119 d
Tropic (not topped)	38,300			6.7			257
Floradel (not topped)	38,300			6.7			257

a. Untopped plants grown from January 22-July 16 in an adjacent experimental area replicated six times.

b. Average of three replications. Means followed by the same letter are no different at the 5% level of probability. Yields from the untopped Tropic and Floradel plants were not statistically compared with other yields.

TABLE 5

INITIAL CAPITAL INVESTMENT COSTS COMPARISON
OF COMPONENTS THAT ARE DIFFERENT FOR THE MUSCLE SHOALS
WASTE HEAT GREENHOUSE SYSTEM (223 m^2)
AND A CONVENTIONAL GREENHOUSE SYSTEM, 1975

Item[a]	Waste Heat	Conventional
CELdek system	$ 1,573	$ 975
Conventional heating system	--	1,353
Fin-tube heater and piping	650	--
Fiberglass attic and recirculation chamber	3,250	--
Exhaust fans and shutters	3,627	1,779
Extra space required	1,200	--
Extra doors	195	--
Total	$10,495	$4,107

a. Installation cost was assumed to be about 30 percent of materials cost.

TABLE 6

ESTIMATED ANNUAL COST COMPARISONS

OF ITEMS THAT ARE DIFFERENT IN THE MUSCLE SHOALS

WASTE HEAT SYSTEM (223 m^2) AND A CONVENTIONAL

SYSTEM OF SIMILAR SIZE, 1975

Item	Cost per Year: Waste Heat System	Cost per Year: Conventional System	Cost per Year: Waste Heat Compared With Conventional
	$	$	$
Initial capital (amortized at 9% for estimated life of item[a])	1,418	618	+800
Operating Costs:			
Fuel (LP gas at $100/$m^3$)	--	2,000	-2,000
Electricity (2.5¢/kWh)	466	316	+150
Maintenance (1 or 5%)[b]	220	150	+ 70
Total Cost	2,104	3,084	-980

a. Ten years was used for estimated life of CELdek, pumps, and motors, except for shutter motors where 5 years was used. Fifteen years was used for fiberglass. Other major structure items were assumed to last 20 years. The salvage values were assumed to be zero.

b. One percent of item cost including installation was used for maintenance on structural items, and 5 percent was used for pumps, motors, etc.

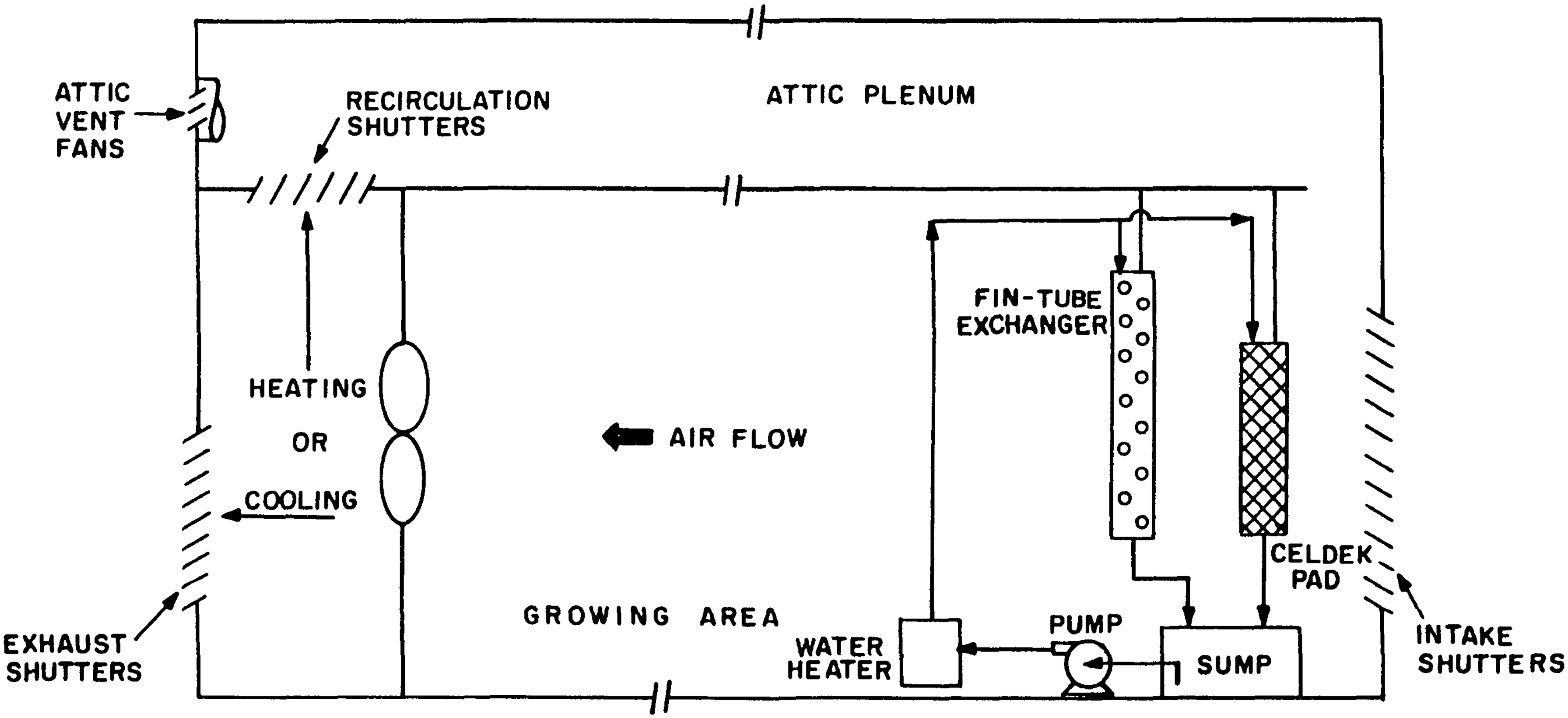

Figure 1. Schematic Drawing of Waste Heat Research Greenhouse, Muscle Shoals, Alabama.

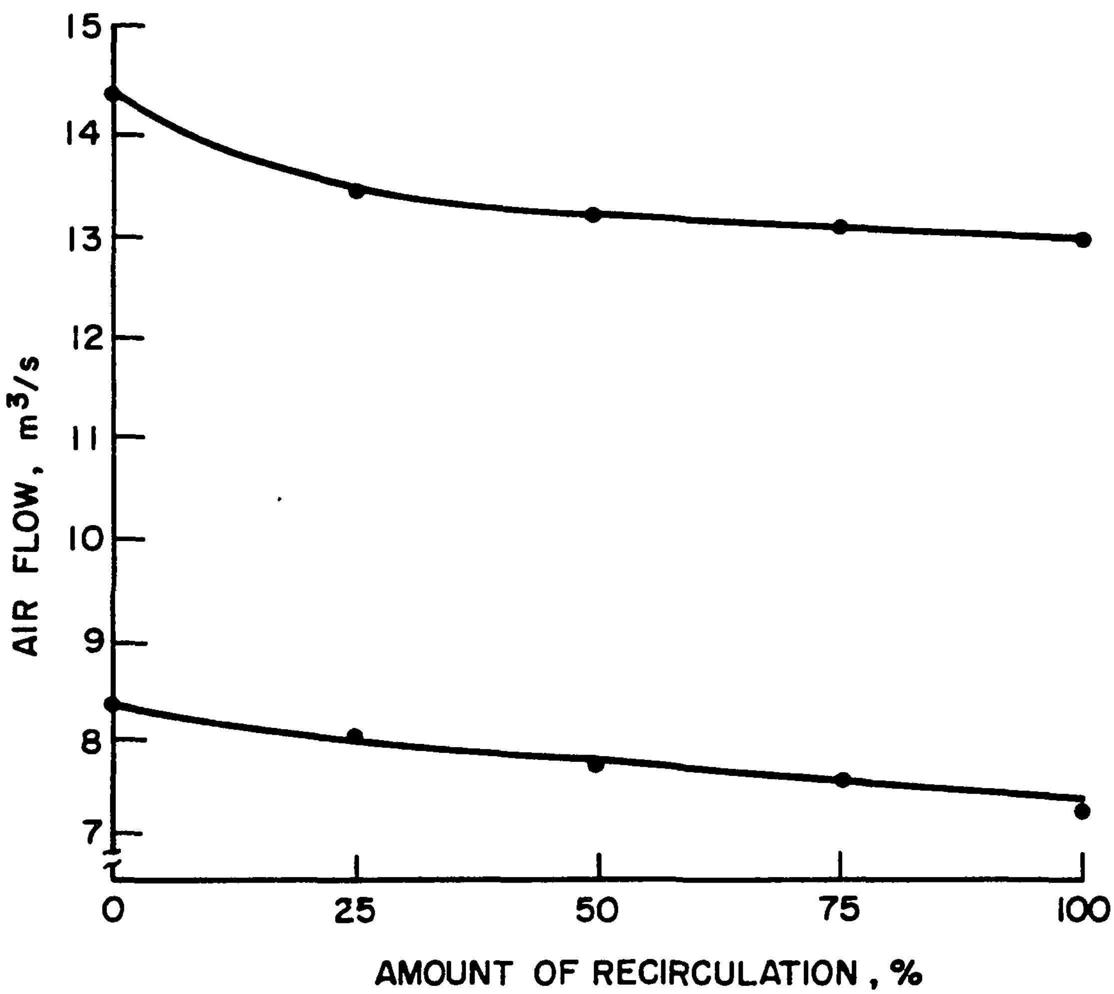

Figure 2. Greenhouse Air Flow Rates as Affected by Amount of Air Recirculation, Waste Heat Greenhouse, Muscle Shoals, Alabama.

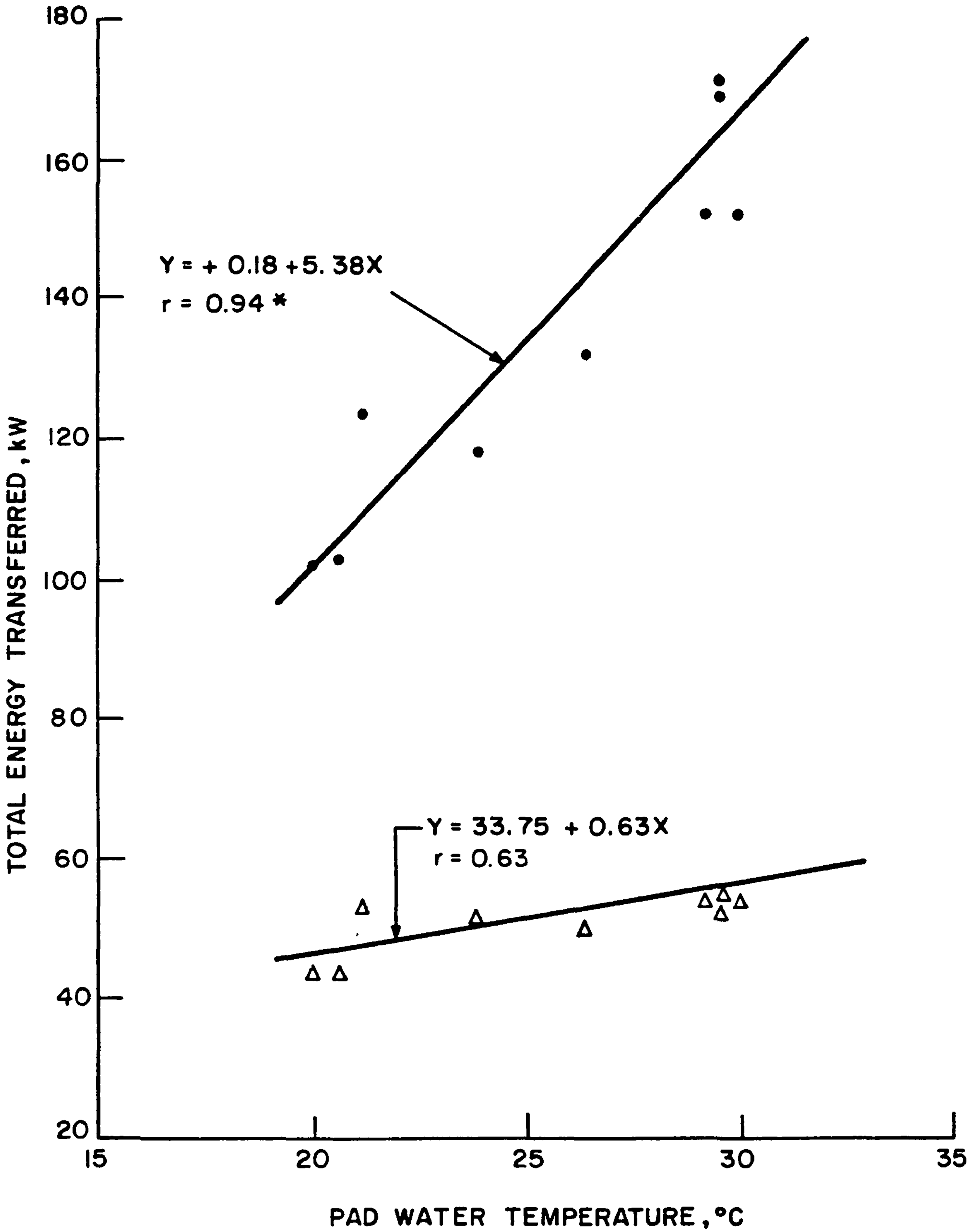

Figure 3. Energy Exchange in the Evaporative Pad with Various Water Temperatures, Waste Heat Greenhouse, Muscle Shoals, Alabama.

*Denotes Significance at 5-Percent Level of Probability.

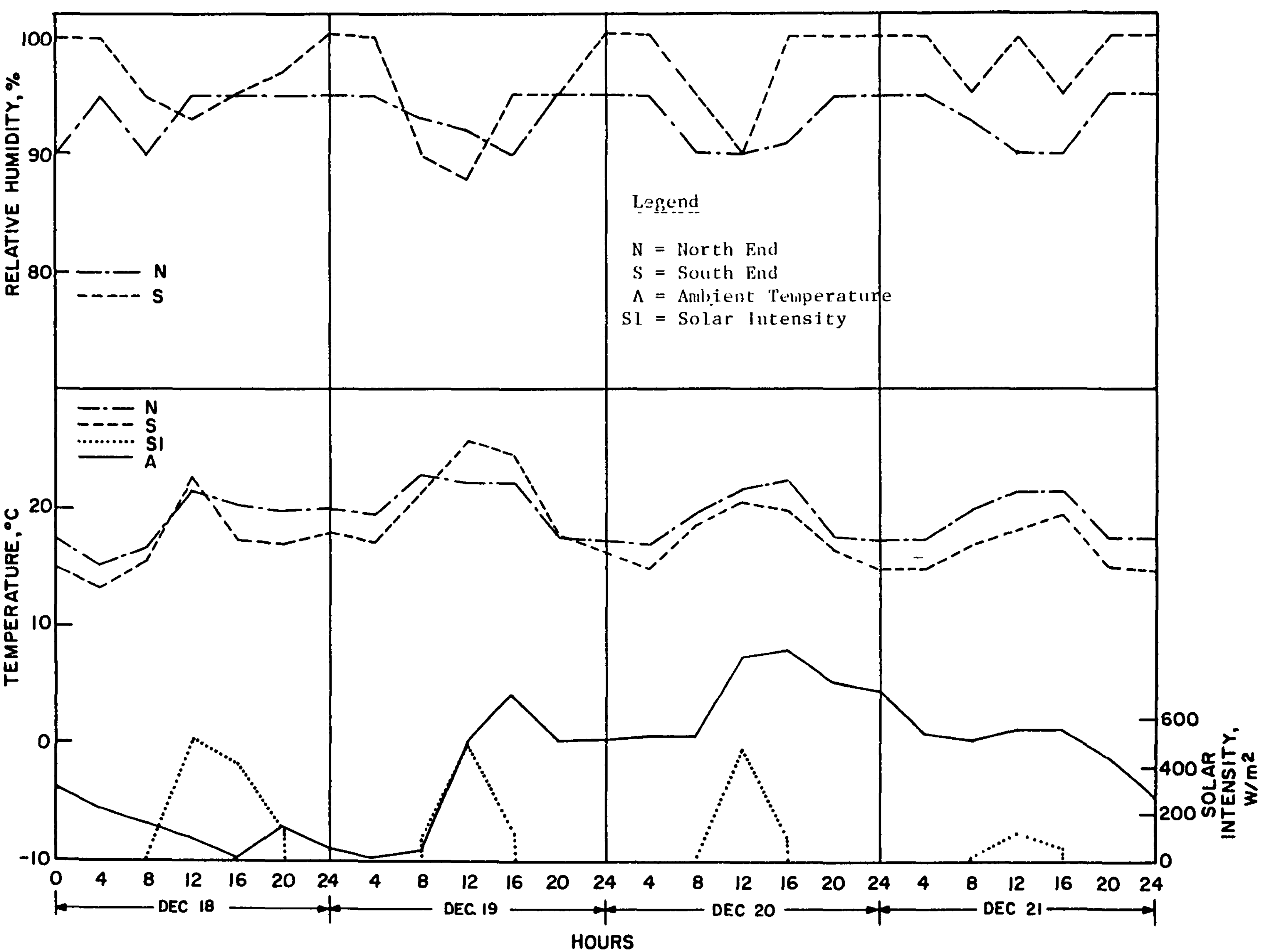

Figure 4. Greenhouse Temperatures, Relative Humidity, and Ambient Conditions During a Typical 4-Day Heating Period, Waste Heat Greenhouse, Muscle Shoals, Alabama.

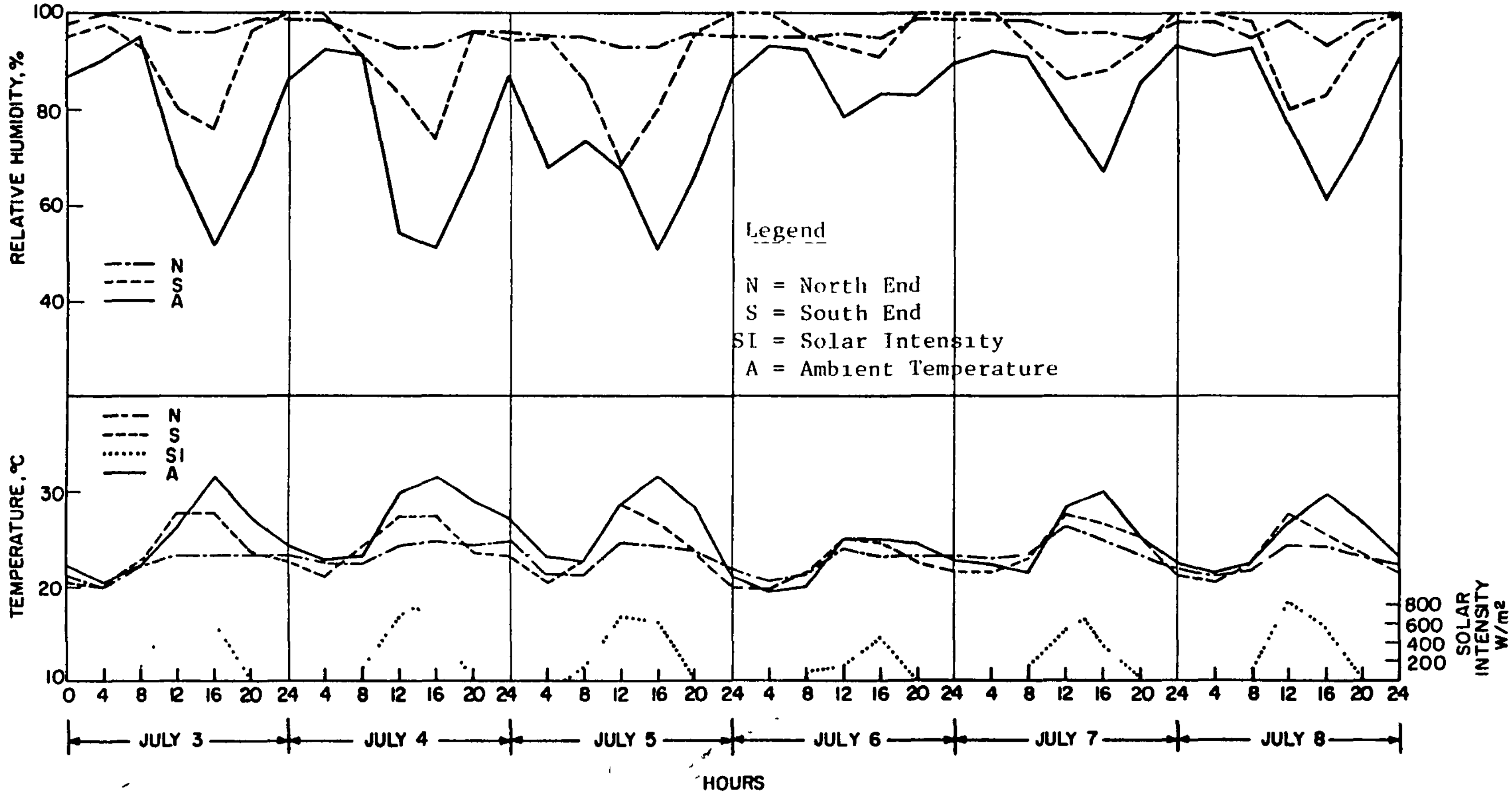

Figure 5. Greenhouse Temperatures, Relative Humidity, and Ambient Conditions During a Typical 6-Day Cooling Period, Waste Heat Greenhouse, Muscle Shoals, Alabama.