AN EVALUATION OF SOLAR ENERGY FOR HEATING A HIGHWAY MAINTENANCE HEADQUARTERS BUILDING

by

Marvin H. Hilton
Senior Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

March 1985
VHTRC 85-R28

ENERGY TASK GROUP

M. H. HILTON, Chairman, Senior Research Scientist, VH&TRC

D. C. HARRIS, TSM & Programs Engineer, FHWA

R. L. HUNDLEY, Environmental Quality Engineer, VDH&T

R. ALLAN LASSITER, JR., Transportation Program Supervisor, State Office of Emergency & Energy Services

C. O. LEIGH, Maintenance Engineer, VDH&T

W. H. MASHBURN, Assist. Professor of Mechanical Engineering, VPI & SU

E. D. SLATE, General Services Supervisor, VDH&T

R. P. STOCKDELL, Senior Electrical Engineer, VDH&T

ADVISOR TO ENERGY TASK GROUP

S. F. LANFORD, Vice-President, Lanford Brothers Co., Inc.

SUMMARY

A highway maintenance area headquarters building having overall dimensions of 64 ft - 8 in by 42 ft - 0 in was equipped with an active solar heating system to assist in heating space and domestic hot water. The solar system was instrumented and its operation monitored for a 15-month period. An evaluation of the data collected indicated that the solar system conserved, on an annual basis, 53,023 kWh of power. At a cost of $0.0387 per kWh, annual savings of $2,052 were realized. A present-value analysis of the cost savings indicated that the investment in the active solar system was very favorable, if the power cost savings are doubled to reflect the potential savings of irreplaceable fossil fuels. If only the direct power cost savings are recognized, the investment in the active solar system is marginal, having a 19-year payback on a 20-year estimated service life. Since the water heater can utilize the solar energy during the full year, it is this aspect of the system that renders the total system economically favorable.

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INTRODUCTION

The use of solar energy to assist in heating highway and transportation facilities has been encouraged by the Department of Energy and the Federal Highway Administration (FHWA) through the sponsorship of Demonstration Project No. 52. Under this promotion, the FHWA awarded the Virginia Department of Highways and Transportation a contract to install a solar system in a new maintenance area headquarters building. One of the requirements of the contract was that the solar system be monitored to determine the energy and cost savings that would be realized from its use. Under this contract the costs of a solar heating system exceeding that of a conventional system are paid for with federal funds. Since the funding contract required that the solar installation be monitored and that monthly and final reports be submitted to the FHWA to cover and evaluate a year of operation of the facility, the Virginia Department of Highways and Transportation requested that the Research Council perform the monitoring and reporting phases of the contract. This present report is the final one on the operation of the solar heated maintenance area headquarters building.

PURPOSE AND SCOPE

The primary purpose of the study was to determine the general operating efficiency and the amount of energy and monetary savings that would accrue from this use of an active solar energy system as used to heat space and water in a maintenance area headquarters building. An additional purpose was to determine if the active solar heating installation was an economically sound investment when used for heating this type of facility.

The typical maintenance area headquarters building is heated by conventional means such as electricity or fossil fuels. In the application of solar heating, the basic size of the building was maintained, with only the slope of the roof being changed somewhat to accommodate the solar collectors. The heating system, of course, was modified to accommodate both the solar and backup systems.

The scope of the study was limited to monitoring the temperatures, times, and flow of the fluid through the solar system; there was no attempt to study the effects of varying the flow rates through the various loops of the system. The system was monitored for approximately 14½ months, exclusive of the time the monitoring equipment was out of service because of breakdowns. Except for two breakdowns, the monitoring of the solar system was reasonably continuous from February 1, 1982, through April 1, 1983. Although only one full year of monitoring was required, several extra months of data were collected and are included in this report.

PROJECT LOCATION AND GENERAL CLIMATIC CONDITIONS

The solar heated maintenance area headquarters building is located in Campbell County, Virginia, several miles south of Lynchburg on Rte. 682. The latitude of this location is approximately $37^{o}25'$. The average annual heating degree days for this region is approximately 4,150, assuming a $65^{o}F$ base temperature. The average daily temperature during the winter months (January, February, and March) is about $39.5^{o}F$, and during the summer (June, July, and August), it is approximately $76.5^{o}F$. The average annual percentage of possible sunshine is approximately 59%.(1) The average solar insolation during the winter months is approximately 950 $Btu/ft^2/day$, and during the summer approximately 1,600 $Btu/ft^2/day$. All of the above averages, of course, vary from year to year and are only representative of what might be expected for the region.

DESCRIPTION OF THE BUILDING AND SOLAR HEATING SYSTEM

The overall dimensions of the maintenance area headquarters building are 64 ft- 8 in by 42 ft -0 in. The building comprises a shop area for the repair and maintenance of vehicles, a service equipment room, a warming area for maintenance workers, an office area, locker room and lavatories, and a room that houses the building's solar and mechanical equipment. The floor plan for the one-story building is shown in Figure 1.

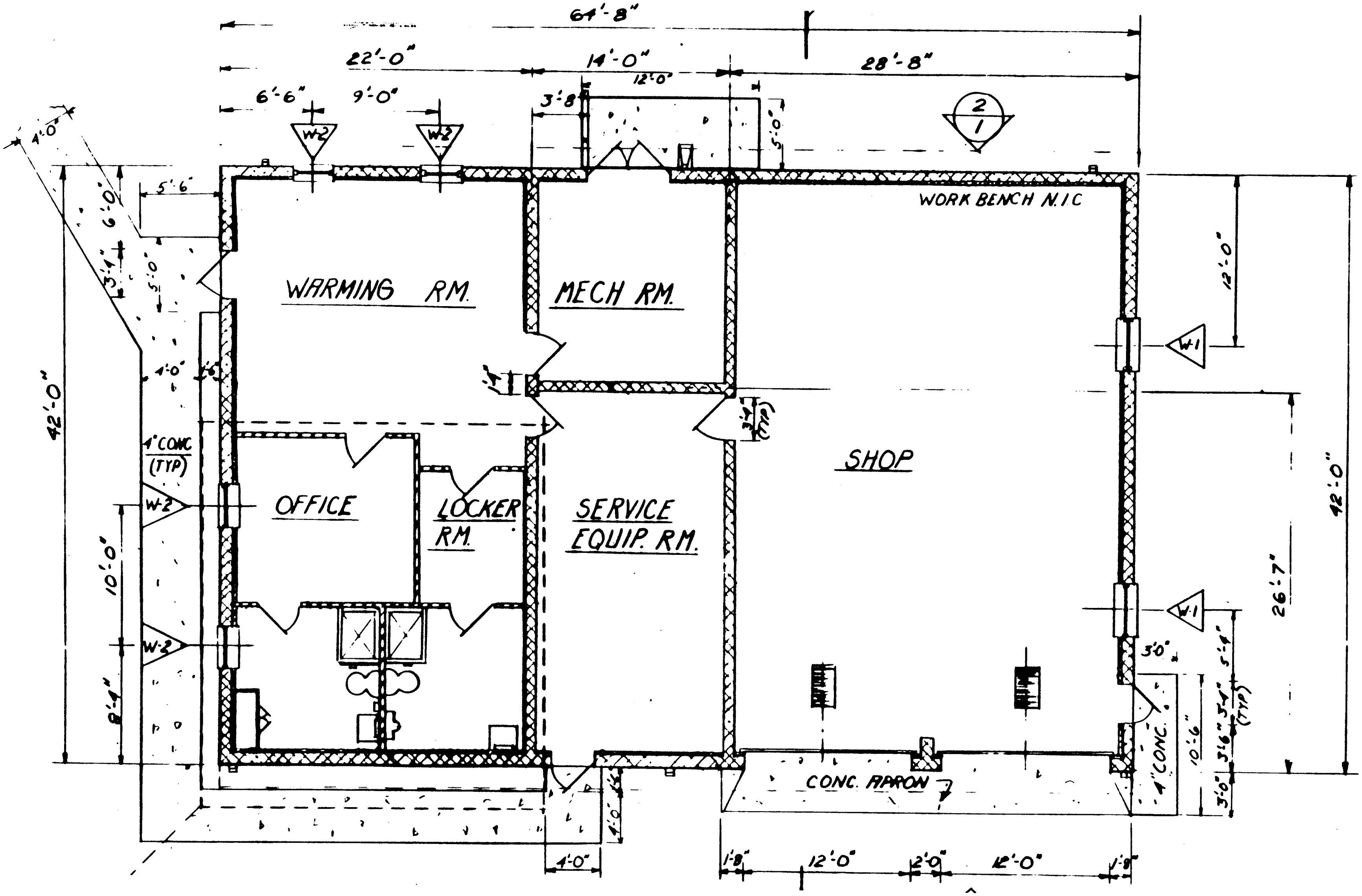


Figure 1. Floor plan for the solar heated maintenance area headquarters building.

Twenty-five solar collectors each having exterior dimensions of 22 1/4 in x 168¼ in and an area of 25 ft^2 are mounted at a 45° angle on the south facing slope of the roof. Therefore, a total collector area of 625 ft^2 is used to supply the solar energy to heat the facility when solar conditions permit. An auxiliary electrical heating system capable of supplying the total heating requirements when necessary is used to supplement the solar system as needed.

The south side of the headquarters building is shown in Figure 2. This view shows the entry doors to the vehicle maintenance area shown earlier in the floor plan of Figure 1. The entries to the office and warming room are located on the west side of the building. Details of the solar collectors and the method of mounting them to the roof are given in Figures A-1 through A-4 of Appendix A. Details of the design of the 1,000 gal solar storage tank, insulation details, and a diagram showing the connections between all elements of the solar heating system are shown in Figures A-5 through A-7.

Figure 2. South face of the solar heated maintenance area headquarters building.

A schematic showing the flow through the various components of the solar energy system is shown in Figure 3. Pump A moves the fluid from the 1,000 gal hot water storage tank to the solar collectors. A differential thermostat (unit 9 in the electrical control layout shown in Figure 4) controls the operation of the solar collector system. Pump B circulates fluid to the heat transfer loop in the water heater. When the thermostat designated unit 5 in Figure 4 detects that the fluid in the solar storage tank is less than its set amount, the heat relay designated unit 4 activates the auxiliary heater. In a similar fashion pump C supplies the fluid to the shop space heater. When the temperature at the shop heater falls below its setting, the thermostat designated unit 3 in Figure 4 activiates pump C. Pump D circulates the heat transfer fluid to the office space heater and is controlled by the thermostat designated unit 16 in the electrical control diagram. When the temperature falls below its predetermined setting for either the office or the shop heater, the associated pump is activated.

A view of the solar storage tank is shown in Figure 5.

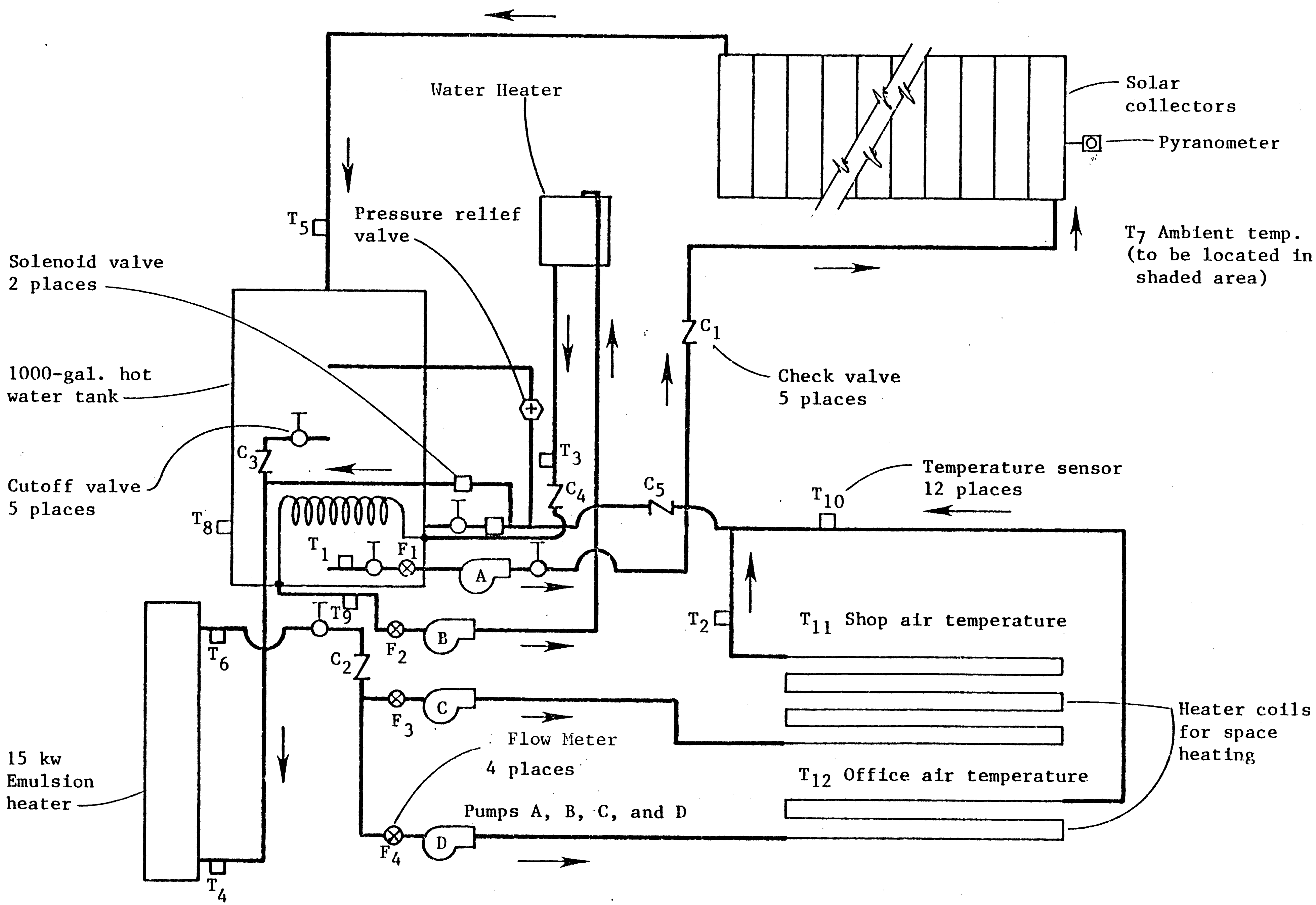


Figure 3. Flow schematic for solar heated building.

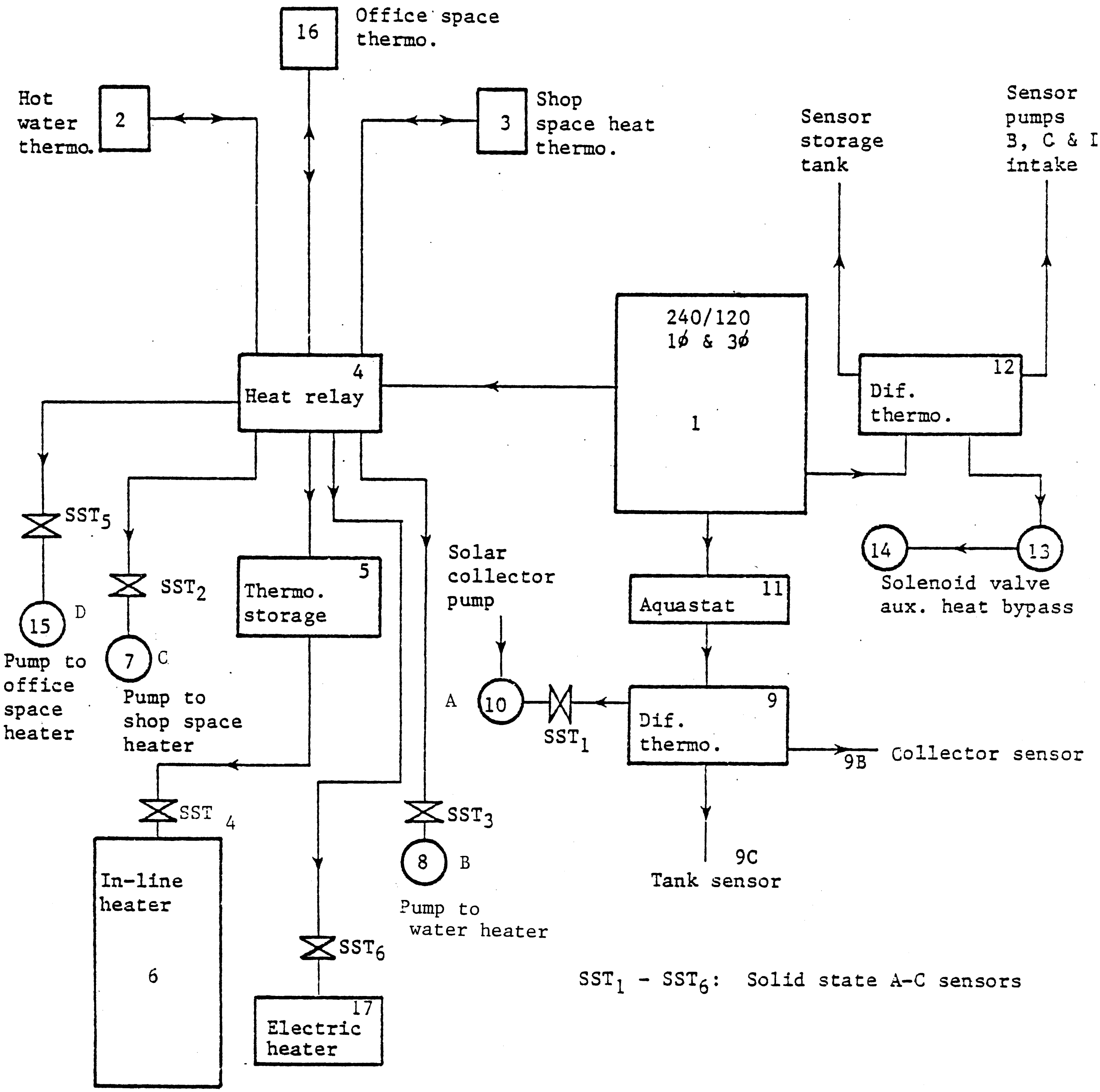


Figure 4. Electrical control layout for solar heated building.

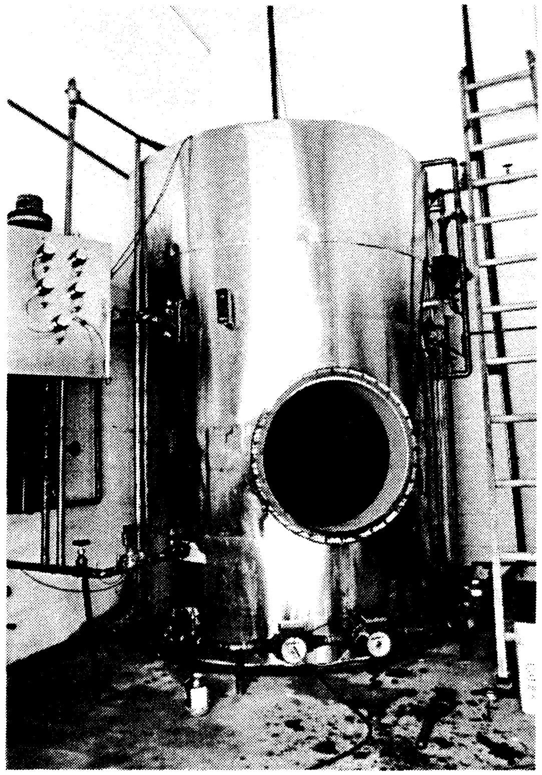


Figure 5. A view of the solar hot water storage tank during installation.

INSTRUMENTATION

The monitoring system for the solar heated maintenance area headquarters building employed a microprocessor to control the monitoring rate of each of the sensors. Twelve temperature sensors were used to establish the heat transfer across the various loops of the system. The temperature differentials of the liquid between strategic points were used to establish the energy supplied and used by the system. Ambient temperature conditions were also monitored. Voltage sensors were used at six locations to determine pump and auxiliary heater usage, and the rate of flow of the heat transfer fluid was measured by flow meters located in each of the four main loops. A pyranometer was installed on the building roof, adjacent to the solar collectors, to measure the incidence of solar radiation. A cassette tape recorder was used to log the data and a tape player was used to replay the data for computer analysis.

Figures 3 and 4 show the locations of all the temperature sensors, flow gages, and the pyranometer. All flow meters were located such that fluid turbulence at the meters could be avoided. The solid state A.C. sensors indicated in Figure 4 as SST_1 - SST_6 were connected to their respective monitoring devices through standard A.C. zip cords and 110 V A.C. outlets that paralleled the power sources for the devices. The flow gages, temperature sensors, pyranometer, and solid-state A.C. sensors were used to monitor the system with the following data being recorded:

(a) The temperature differentials for each loop during operation of the pump. The temperature differentials for pumps A, B, C, and D were measured, respectively, by sensors T_1 and T_5, T_3 and T_9, T_2 and T_6, and T_6 and T_{10}. Sensors T_4 and T_6 measured the thermal differential across the in-line heater.

(b) The time of operation of the in-line heater and each pump in the system.

(c) Solar incidence.

The flow of the heat transfer fluid through each of the four loops of the system was measured with a flow meter, and the flow values were used as constants in calculating the energy collected and used by the system. The electrical power consumption of the pumps, the water heater element, and the auxiliary heater was determined based on the time that these units were in operation over a given monitoring period.

The temperature measurements were recorded by a microprocessor. The initial temperatures at each pair of sensors for each loop and the auxiliary heater were recorded as described in item (a) above. The two temperatures for each loop were recorded approximately 30 seconds after the pump was activated and were rechecked and recorded, along with the time of day, any time the temperature at a sensor changed by two degrees. Pyranometer readings were recorded and the values used to determine the amount of solar radiation during the transfer of energy from the collectors to the fluid. Therefore, the duration of collector activity and the solar incidence values were recorded by the microprocessor whenever the solar pump (pump A in Figure 3) was active.

The solar storage tank temperature, T_8, was recorded at the initial start-up of the system and at the end of each day. The ambient air temperature in the office and shop areas and exterior to the building were checked every 10 minutes and recorded whenever a change of 2°F occurred. Any failures in the electrical power supply were recorded at the time of occurrence.

The data were collected and recorded on a cassette tape which was picked up and replaced at two- or three-week intervals. The data were later read back and computer analyzed. The microprocessor and recording equipment were located in the mechanical room of the building as shown in Figure 6.

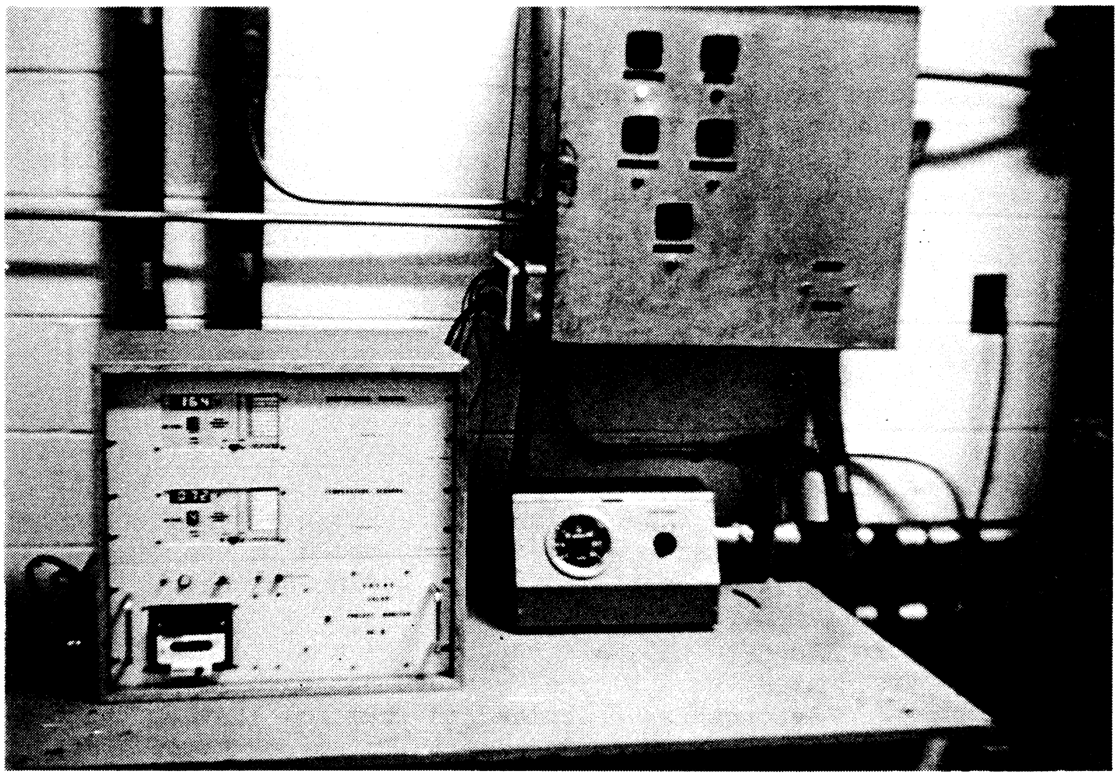


Figure 6. The microprocessor and recording equipment (left foreground); flow meter (center foreground).

DATA PROCESSING AND ANALYSIS

The data were analyzed on a CDC CYBER 172 computer using FORTRAN programming. The temperature differentials, flow values, and pump on times were used to establish the number of Btu's supplied by the solar collectors and the auxiliary heater, and the number of Btu's used to heat the building and the water. The solar intensity data provided the threshold value and the levels necessary for the operation of the collector system. Reference ambient temperatures were taken during all pump operations. With these data, the following items could be monitored or calculated.

1. Total solar energy incident in the plane of the collectors

2. Solar energy transferred from the collectors to the fluid

3. Space heating and water heating load demands

4. Solar energy contribution to the heating requirements

5. Auxiliary heater's contribution to the heating requirements

6. Auxiliary heater's fuel consumption

7. Electrical energy used by the auxiliary heater and solar system pumps

8. Interior and exterior ambient temperatures

9. Electricity and cost savings

10. Downtime of the system due to electrical power failures

Most of the above items were summarized on daily and monthly reports generated by the CDC computer. The monthly summary report for February 1983 is shown in Figure 7. This summary was developed from the data collected on the cassette tapes and from the monthly performance calculations described later. The computer was also programmed to portray the average daily values of the ambient temperature, irradiation, collector activity, solar energy added, energy added, energy used, energy lost, electricity used, and solar contribution to useful energy. Example graphs of these variables for the month of February are shown in Figures B-1 through B-9 of Appendix B. Each graph shows the daily values for each day of the month of February. An integrated summary of some of these data is given in the monthly performance report shown in Figure 7. The monthly performance reports, including the data presented in graphic form, were submitted to the FHWA earlier.

A general view of the solar energy situation for each day of any given month could be obtained by perusing the data typical of that illustrated in Appendix B. Hence, one could review these data to determine the number of days during a given month that solar energy made a significant contribution to the energy requirements of the building.

The monthly performance report includes an estimate of the solar contribution to the heating of the building. Electrical energy and costs savings are calculated based on two methods of evaluation. These two methods are defined below.

The monthly performance reports such as the example shown in Figure 7 were developed from the data collected on the cassette tapes. The format for the monthly report shown was also used for daily summaries whenever these were desired. The calculations that follow were programmed to be performed by the computer and printed out as the monthly summaries of the solar system's performance.

ENVIRONMENTAL FACTORS:

AMBIENT TEMPERATURE	IRRADIATION ≥ 100	IRRADIATION USED
37.9 DEGREES F	768.2 KWH	1164.5 KWH
	SOLAR DUTY CYCLE	COLLECTOR ACTIVITY
	4.9 %	13.3 %

ENERGY ADDED TO THE SYSTEM:

SOLAR	INLINE HEATER	DOMESTIC HOT WATER
2404.6 KBTU'S	2981.1 KBTU'S	.0 KBTU'S

ENERGY USED BY THE SINKS:

SHOP SPACE HEATER	OFFICE SPACE HEATER	DOMESTIC HOT WATER
1853.7 KBTU'S	3334.6 KBTU'S	173.6 KBTU'S

ELECTRICITY USED BY THE SYSTEM:

CIRCULATION PUMPS	INLINE HEATER	DOMESTIC HOT WATER
85.6 KWH	1746.7 KWH	.0 KWH

TOTALS:

ENERGY ADDED	ENERGY USED	ELECTRICITY USED
5385.7 KBTU'S	5362.0 KBTU'S	1832.3 KWH'S

ENERGY LOST BY THE SOLAR NETWORK: 95.9 KBTU'S

TEMPERATURE OF THE BUILDING: OFFICE: 68.3 F SHOP: 67.8 F

THERE WERE 0 POWER OUTAGES FOR A TOTAL DOWNTIME OF .0 MINUTES

IMPACT OF SOLAR CONTRIBUTION

	SOURCE METHOD	SINK METHOD
PORTION OF USEFUL ENERGY SUPPLIED BY THE SOLAR SYSTEM	55.2 %	58.2 %
CONVENTIONAL ENERGY SAVED	8185.6 KWH	8131.3 KWH
DOLLARS SAVED (.0387/KWH)	316.76	314.65

Figure 7. Typical monthly solar performance report for area headquarters building.

Environmental Factors

The average monthly ambient temperature was calculated from the daily averages by relationship as

$$A_T = \frac{\sum_1^N \frac{\sum_1^M T_A t}{24 \text{ hours}}}{N},$$

where

A_T = average ambient temperature,

T_A = ambient temperatures,

t = number of hours at a given temperature,

M = number of temperature changes in a 24-hr period, and

N = number of days.

Irradiation greater than 100 is defined as the summation of the kWh of solar energy above the 100 Btu/ft^2 level.

$$S = \sum_1^N \sum_1^M S_I t K,$$

where

S = total solar energy > 100 Btu/ft^2

S_I = individual measurements > 100 Btu/ft^2,

M = number of measurements per 24 hr,

N = number of days

t = time at a given irradiation level, and

K = Btu to kWh conversion factor.

The solar radiation used was computed by summing the kWh of solar energy available to the collectors while they were active. That is,

$$S_U = \sum_{1}^{N} \sum_{1}^{M} S_I t,$$

where

S_U = solar energy collected,

t = time that solar intensity was at a given level during collector activity,

S_I = solar intensity during periods when the collectors were active,

N = number of days, and

M = number of times the collector was active.

The activity of the collectors is related to the intensity of the solar radiation and was measured as the average daily percentage of activity over the monthly period.

$$C_A = \frac{\sum_{1}^{N} \sum_{1}^{M} \frac{t\,(100)}{24}}{N},$$

where

C_A = collector activity, in percent,

M = number of times the collector was active, and

t = time of collector activity, hr.

Energy Added to the System

The amount of solar energy added to the system was monitored by measuring the temperature differential between the entrance and exit to the collectors and the flow rate through them.

$$S_E = \sum_1^N \sum_1^M F_S (T_o - T_i) t,$$

where

S_E = solar energy in Btu,

F_S = flow through the collectors,

T_i = entrance temperature of fluid,

T_o = exit temperature of the fluid, and

t = time interval at a given T_i and T_o.

The energy supplied by the in-line heater was measured by monitoring the temperature differential across the heater and the flow through it.

$$H = \sum_1^N \sum_1^M F_H (T_o - T_i) t,$$

where

H = heater energy in Btu, and

F_H = flow through the heater.

The energy supplied by the electrical heating element in the water heater is a conversion of kWh's used to Btu's used.

$$W = \frac{\sum_1^N \sum_1^M W_R}{K},$$

where

W = water heater energy in Btu,

W_R = rated wattage of the heating element, and

K = kWh to Btu conversion factor.

Energy Used

The energy used by the shop space heater was determined by monitoring the temperature differential across the heater and the flow through it.

$$H_S = \Sigma_1^N \Sigma_1^M F_H (T_6 - T_2) t,$$

where

H_S = energy used by shop heater in Btu,

F_H = flow through the heater,

T_6 = entrance temperature of the fluid,

T_2 = exit temperature of the fluid, and

t = time interval at a given $T_6 - T_2$.

The energy used by the office space heater was determined by monitoring the temperature differential across and the flow through the heater.

$$H_o = \Sigma_1^N \Sigma_1^M F_H (T_6 - T_{10}) t,$$

where

H_o = energy used by the office space heater in Btu,

T_6 = entrance temperature of the fluid, and

T_{10} = exit temperature of the fluid.

The energy used by the water heater was determined by monitoring the temperature differential across and the flow through the water heater.

$$H_w = \sum_1^N \sum_1^M F_H (T_9 - T_3) t,$$

where

H_w = energy used by the water heater in Btu,

T_9 = entrance temperature of the fluid, and

T_3 = exit temperature of the fluid.

Electricity Used

The pumps that circulate the fluid operate only during the acquisition or the use of energy. Consequently, the energy used by the pumps was determined for the period of time that each was in use.

$$P_x = \sum_1^N \sum_1^M W_x t_x,$$

where

P_x = energy used by a given pump in kWh,

W_x = pump rating in W,

t_x = time that a given pump was on, and

x = pump number (Figure 3).

The in-line heater was used only when the solar system was not able to supply sufficient energy to meet the heating requirements of the sinks. The energy used by the heater was determined for the time that it was in use as

$$H = \sum_1^N \sum_1^M W_H t_H,$$

where

H = energy used by the heater in kWh,

W_H = rating of the heater in W, and

t_H = time the heater was on.

The water heater uses electricity only when insufficient solar energy is available. Its electricity usage was determined by

$$W_D = \sum_1^N \sum_1^M W_R t_D,$$

where

W_D = energy used by the water heater in kWh,

W_R = rating of the water heater in W, and

t_D = time the water heater element was used.

Energy Lost by the System

The energy lost by the system was determined by summing the energy added and the initial reserve energy and subtracting the sum of the energy used by the sinks and the final reserve energy.

$$E_L = \sum_1^N KW_f(T_I - T_F) + (S_E + H - H_S - H_o - H_W),$$

where

E_L = energy lost by the system,

K = Btu conversion factor,

W_f = weight of the solar fluid,

T_I = initial reserve temperature, and

T_F = final reserve temperature.

All of the factors in the above equation are daily values. Electricity consumption was not included in this calculation.

Temperature of the Building

The temperature of the office portion of the building was determined and reported as a monthly weighted average of the periodic measurements of the office air temperatures.

where
$$O_T = \frac{\sum_1^N \frac{\sum_1^M T_{12} t}{24}}{N},$$

O_T = average monthly office temperature, and

T_{12} = periodic office air temperature measurements.

The temperature of the shop portion of the building was determined and reported as the weighted average of the periodic measurements of the shop air temperature.

$$G_t = \frac{\sum_1^N \frac{\sum_1^M T_{11} t}{24}}{N}$$

where

G_T = average monthly shop temperature, and

T_{11} = periodic shop air temperature measurements.

Impact of Solar Contribution

The impact of the solar contribution to the total heating requirement of the system can be viewed from two perspectives. The first was designated as the source method and considers the solar input side of the system. This method assumes that all the solar energy is useful and could be converted directly into savings. The second method was designated the sink method and considers the output side of the system. The sink method assumes that the only savings derived from the solar energy is the energy used that is not provided by the in-line heater.

The portions of the useful energy supplied by the solar system as defined by the source and sink are methods given by

$$E_1 = \frac{\left[\sum_{1}^{N} \frac{S_E}{S_E + H + W}\right] 100}{N},$$

$$E_2 = \frac{\left[\sum_{1}^{N} \frac{H_s + H_o + H_w - (H + W)}{H_s + H_o + H_w + W}\right] 100}{N},$$

where

E_1 = useful solar energy supplied in percent (source method), and

E_2 = useful solar energy supplied in percent (sink method).

The savings in conventional energy as determined by the source and sink methods, respectively, are $\sum_1^N KS_E$ and $\sum_1^N K\ (H_s + H_o + H_w - H - W)$, where K is a Btu to kWh conversion factor. The product of the cost per kWh and either of these two expressions yields the power cost savings for a given month. These savings estimates are, of course, based on the data obtained and the method of evaluation.

RESULTS

The solar installation was scheduled to be continuously monitored for a one-year period of operation. After some mechanical difficulties with the drive shaft of the cassette tape recorder and several additional debugging operations, the monitoring system was put in operation in February 1982. Because of several power failures associated with electrical storms in the area and a 12-day breakdown of the microprocessor in December 1982, the system was monitored over a 15-month period, and because of malfunctions and other outages, the monitoring equipment was inoperative for approximately the equivalent of half a month. Actual monitoring time, therefore, was slightly more than 14 months. In addition to the above problems, the pyranometer readings were erratic during the last few months of the monitoring period. Although it is not known exactly when the problem began there was little indication of problems with the solar incidence readings during the first 12 months of monitoring. When the pyranometer was removed near the end of the study it was apparent that moisture had penetrated the device and probably caused the erratic readings obtained. It should be noted, however, that these data do not affect the energy data provided by the major portion of the monitoring system.

The monthly records of the daily operation of the solar system were developed and summarized as discussed earlier and illustrated in Figure 7 and in Figures B-1 through B-9 of Appendix B. These data were transmitted to the FHWA Demonstration Projects Office as they were developed. Since the quantity of data is too great to present in this report, only an overall summary of the monthly performance data is presented here.

Environmental Data

The average monthly ambient air temperatures and the average monthly temperature of the office and shop areas of the building are given in Table 1. The average monthly ambient temperatures ranged from 35.8°F for January 1983 to 78.7°F during July 1982. This yearly average temperature range is reasonably close to that normally expected for that locality, as was discussed earlier. The monthly averages for the interior office space of the building ranged from 68.3°F in February 1983 to 74.6°F in May 1982. As would be expected, the average temperatures in the shop area of the building were lower than those for the office area during the colder months and higher than those for the office area during the warmer months. These average monthly temperatures ranged from 64.1°F to 83.4°F.

During the course of the monitoring period, 19 power outages, which varied from one minute to more than four days, were recorded as shown in

Table 1. The majority of the power failures were short in duration -- lasting only a few minutes. Other than the failure that lasted for more than four days, the longest power outage was less than three hours. The total time lost to the power failures during the 15-month monitoring period was 108.6 hours.

Table 1

Average Monthly Ambient and Interior Termperatures

Year	Month	Average Ambient Temp.	Average Building Temp.		Power Outages	
			Office	Shop		
		°F	°F	°F	No.	Time, hr
1982	February	39.5	72.1	65.7	3	0.43
	March	46.2	71.8	66.6	-	-
	April	54.9	70.5	70.0	-	-
	May*	71.4	74.6	78.2	2	100.6
	June	73.5	74.1	79.1	1	0.04
	July	78.7	73.7	83.3	1	0.02
	August	74.4	73.4	83.4	1	0.02
	September	67.8	72.8	80.2	3	0.08
	October	57.7	73.3	75.5	-	-
	November	49.2	71.0	70.8	2	2.89
	December**	39.9	70.1	64.8	-	-
1983	January	35.8	70.1	64.1	3	1.47
	February	37.9	68.3	67.8	-	-
	March	47.2	70.2	71.3	1	1.31
	April	53.6	70.8	68 4	2	1.72

* The monitoring equipment was inoperative for over 100 hours due to power outages related to electrical storms.

** The monitoring equipment was inoperative for 12 days due to technical difficulties.

Energy Supplied to the Heating System

The energy supplied to the heating system by the solar and the auxiliary electrical heater is given in Table 2. During the monitoring period the solar system added 25,213 kBtu of energy to the storage tank. The auxiliary electrical heater supplied 12,714 kBtu to the heating requirements. The total energy added to the system by both of these sources was 37,387 kBtu. Therefore, for the 15-month monitoring period 67% of the energy was supplied by the sun. Considering only the 12-month period from February through January, 18,617 kBtu, or 70%, of the total of 29,382 kBtu were supplied by the sun. Considering only the colder months of December, January, February, and March, 50% of the energy was supplied by the sun. On an annual basis, however, it is apparent that solar energy supplied two-thirds of the energy required to heat the building and the domestic hot water supply.

It can be noted from Table 2 that no energy was required from the auxiliary heater for six consecutive months (May through October). During this period only minor heating of the building was required due to the warmer ambient temperatures. Therefore, the demand for energy during six months of the year was minimal compared to the capability of the collectors to provide energy.

Table 2

Energy Supplied to the Heating System

Year	Month	Collector Activity, %	Solar, kBtu	Electrical Heater, kBtu	Total Added, kBtu
1982	February	13.4	2,527	2,273	4,800
	March	12.8	2,480	1,376	3,856
	April	8.7	1,526	233	1,759
	May*	8.1	1,098	0	1,098
	June	7.1	1,010	0	1,010
	July	7.5	1,062	0	1,062
	August	8.0	1,261	0	1,261
	September	7.9	1,115	0	1,115
	October	8.1	1,269	0	1,269
	November	9.7	1,632	118	1,750
	December**	9.9	1,174	1,392	2,566
1983	January	13.1	2,463	2,465	4,928
	February	13.3	2,405	2,981	5,386
	March	11.0	2,183	1,073	3,256
	April	10.9	2,008	263	2,271
	TOTALS		25,213	12,174	37,387

* The monitoring equipment was inoperative for over 100 hours due to power outages related to electrical storms.

** The monitoring equipment was inoperative for 12 days during December due to technical problems.

Energy Used to Heat Space and Water

The quantities of energy used to heat the office and shop areas of the building and to provide domestic hot water are reported in Table 3. For the full 15-month monitoring period 33,811 kBtu of energy were used to meet these heating requirements. This is approximately 10% less than the amount of energy supplied to the system as reported in Table 2. While the difference between the energy supplied and the energy used cannot be specifically accounted for, it is probably due to normal losses in the pipelines and to some variation between the actual flow rates and those used in the calculations. For example, the main feeder line from the storage tank feeds both pumps C and D as was shown earlier in Figure 3. The flow rates through these pumps vary from normal whenever both are operating simultaneously. While this possibility was accounted for in the data analysis, some irregularity in the flows would probably occur when both pumps were operating simultaneously. It should be noted, however, that an 11% difference between the energy supplied and the energy used was reported earlier in the study of a solar heated asphalt tank.(1) Thus, the approximately 10% difference found in this study is in general agreement with that found for the solar heated asphalt tank.

Of the total of 33,811 kBtu of energy used, 7,792 kBtu were used by the shop, 22,890 kBtu by the office and 3,129 kBtu's by the domestic water heater. During the months of June through September, no energy was used by either the shop or the office areas; and during May, October, and November, little or no energy was used to heat the shop area. On the other hand, the domestic water heater consumed slightly more energy during the June through October period than during the remainder of the year. This is probably indicative of the greater use of hot water by the maintenance workers during the warmer months of the year when maintenance activities are the greatest. It is clear, however, that the majority of the energy demand during the five or six warmer months of the year was by the domestic hot water system. On an annual basis, however, the office heating consumes approximately two thirds of the energy used by the building.

Table 3

Energy Used by the Office, Shop, and Water Heaters

Year	Month	Space Heaters Shop, kBtu	Space Heaters Office, kBtu	Water Heater, kBtu	Total Used, kBtu
1982	February	1,100	3,929	127	5,156
	March	602	3,063	210	3,875
	April	227	952	211	1,390
	May	21	81	108	210
	June	0	0	255	255
	July	0	0	273	273
	August	0	0	305	305
	September	0	0	296	296
	October	0	292	302	594
	November	1	1,422	225	1,648
	December	2,277	1,665	62	4,004
1983	January	1,013	4,123	128	5,264
	February	1,854	3,335	174	5,363
	March	632	2,307	225	3,164
	April	65	1,721	228	2,014
	TOTALS	7,792	22,890	3,129	33,811

Electricity Used by the System

The electricity used by the circulation pumps, the auxiliary in-line heater, and the domestic water heater is summarized for the 15-month period of study in Table 4. The quantities shown were all calculated from the power rating of the electrical unit being considered and the time that the unit was in operation. Although the electrical usage of the facility was metered, those quantities are of little value to compare with the calculated electrical comsumption of the solar support units since the lighting, cooling, gasoline and diesel fuel pumps, power tools, etc., are included. In the earlier study of the solar heated asphalt storage tank it was found the the metered electricity used was about twice that of the calculated quantity where the asphalt pump and the monitoring equipment power requirements were not included in the calculated values. In the present study a similar comparison can be made from the measured quantity of energy furnished by the in-line auxiliary heater. The heater supplied 12,174 kBtu to the system (Table 2). This is equivalent to 3,567 kWh of energy output to the system. Based on the power rating of the heater, it consumed 6,821 kWh of electricity. Accordingly, the energy output was about 52% of the rated electrical energy input.

Table 4

Calculated Quantity of Electricity Used by the Circulation Pumps, In-line Heater, and Water Heater

Year	Month	Circulation Pumps, kWh	In-line Heater, kWh	Water Heater, kWh	Total
	February	74	1,258	0	1,331
	March	56	735	0	791
	April	30	128	0	158
	May	21	0	0	21
1982	June	16	0	0	16
	July	159	0	0	159
	August	260	0	0	260
	September	18	0	0	18
	October	20	0	0	20
	November	27	57	0	84
	December	50	787	0	837
	January	79	1,379	0	1,458
1983	February	86	1,747	0	1,833
	March	47	605	0	652
	April	32	125	0	157
	TOTALS	975	6,821	0	7,796

Additional data from Table 4 indicate that the circulation pumps consumed 975 kWh of power and the water heater consumed no additional power during the monitoring period. The zero electrical usage by the water heater indicates that the solar collector area is much more than that needed during the six summer months of the year when the major demand for energy is from the water heater. Since the hot water system, as designed, draws its energy from the energy storage tank, which in turn is partially supplied by the in-line auxiliary heater, it is difficult to determine what its electricity consumption might have been had it been designed as a separate system.

As a final observation from Tables 2 and 4, it can be noted that 25,213 kBtu (7,388 kWh) of solar energy were collected. All the circulation pumps consumed 975 kWh of electrical energy -- or about 13% of the free energy obtained from the sun. This percentage would probably have been considerably lower had there been some use for the energy-collecting capacity of the system during the warmer months.

Energy Conserved

The electrical energy saved by the solar system was calculated based on two perspectives. As described earlier, one perspective was defined as the source method and the other as the sink method. The results of the source method of evaluation are summarized in Table 5. This method indicated that the solar system saved 85,790 kWh of electrical energy over the 15-month monitoring period. At a cost of $0.038 per kWh, this would result in savings of $3,319.78. Considering only the savings in electrical energy accruing between February 1, 1982, and January 31, 1983, 63,339 kWh of electrical energy were saved. Therefore, on an annual basis, $2,451.22 were saved.

Table 5

Energy and Monetary Savings by the Source Method of Evaluation of the Solar System

Year	Month	Useful Solar Energy, %	Electrical Energy Saved, kWh	Savings, Dollars
	February	52.1	8,602	$332.87
	March	71.2	8,442	326.69
	April	82.7	5,192	200.93
	May	100.0	3,733	144.45
1982	June	100.0	3,435	132.91
	July	100.0	3,610	139.71
	August	100.0	4,289	165.96
	September	100.0	3,793	146.76
	October	100.0	4,315	166.97
	November	94.6	5,554	214.91
	December	59.2	3,994	154.54
	January	53.5	8,381	324.32
1983	February	55.2	8,186	316.76
	March	68.1	7,432	287.58
	April	83.6	6,833	264.42
	TOTALS		85,790	3,319.78

* A cost of $0.0387 per kWh was used for this calculation. The rate being charged at the end of the study was $0.049 per kWh.

The savings resulting from the sink method of analysis are summarized in Table 6. By this method the calculated energy saved was 74,282 kWh, which yielded a savings of $2,874.44 over the 15-month period. On an annual basis, between February 1, 1982, and January 31, 1983, the savings were 53,023 kWh, for a monetary savings of $2,052.

The difference between the annual savings calculated by the source method and that calculated by the sink method is about $400, with the source method yielding the greater savings. The sink method, however, is the more realistic approach to evaluating the energy savings since it considers only the solar energy actually put to use. The source method basically assumes that all the solar energy collected is useful. During the colder months this may be a reasonable assumption since on many days the collectors cannot supply the full energy demands but all the energy collected can be used. During the warmer months, however, the collectors are capable of collecting much more energy than is needed; so, much of that energy collected would likely be lost before it can be put to use. This fact can be supported by comparing the data. From Tables 5 and 6 it can be seen that the source method yields much greater savings during the warmer months of the year than does the sink method. The more conservative sink method considers only the energy that was used during those warmer months rather than the amount made available by the solar collectors. The source method of analysis, therefore, does give an indication of the energy that is wasted for lack of use during the warmer periods of the year. Thus, the source method data for the warmer months are simply indications that the solar collector area is much greater than that needed to supply energy for the domestic water heater alone. At any rate, the sink method of analysis yields the most realistic value for annual savings; i.e., $2,052.

Table 6

Energy and Monetary Savings by the Sink Method of Evaluation of the Solar System

Year	Month	Useful Solar Energy, %	Electrical Energy Saved, kWh	Savings*, Dollars
1982	February	60.0	9,846	$380.99
	March	74.2	8,536	330.32
	April	83.3	3,949	152.79
	May	90.3	1,087	42.08
	June	100.0	872	33.76
	July	100.0	932	36.07
	August	100.0	1,041	40.28
	September	100.0	1,010	39.08
	October	100.0	2,030	78.56
	November	92.5	5,224	201.14
	December	62.6	8,936	345.78
1983	January	56.1	9,560	369.94
	February	58.2	8,131	314.65
	March	72.7	7,144	276.44
	April	87.1	5,984	231.56
	TOTALS		74,282	2,874.44

* A cost of $0.0387 per kWh was used for this calculation. The rate being charged at the end of the study was $0.049 per kWh.

ECONOMIC ANALYSIS

The additional cost of the solar system beyond that which a conventional system would have cost was \$25,101.50. This amount included a cost for insulation that was considered to be beyond that which would normally be used as well as the cost of stronger than ordinarily used roofing trusses needed to support the solar collectors.

To give recognition to fringe benefits of alternative uses of irreplaceable fossil fuels, the Demonstration Projects Division of the FHWA suggests that the savings in fuel costs be doubled for the economic analysis. Therefore, the \$2,052 annual energy costs savings indicated by the data could be taken as \$4,104 for the analysis. When the study began, the cost per kWh being charged by the utility for the building location was \$0.0387. At the end of the study, a cost of \$0.049 per kWh was being charged. Thus, the power costs increased by 27% in the approximately 3-year period following construction of the facility. The annual fuel price escalation rate of 10% that was originally estimated was very close to that which occurred during the time period. Therefore, the annual fuel price escalation rate of 10% over the estimated life of the installation will be used.

The present value analysis is based on the following:

Solar component life, n	= 20 years
Nominal interest rate, r	= 12% per year
Fuel price escalation rate, r_e	= 10% per year
Inflation rate (other than fuel), r_i	= 5% per year
Initial cost per kWh	= \$0.0387
Assuming power is generated by fossil fuels (2 x \$0.0387)	= \$0.0774

The present value, PV, of the costs savings resulting from the use of the solar system is given by the relationship

$$PV = A_s e^{-r_e} \frac{e^{n(r_e - r)} - 1}{1 - e^{-(r_e - r)}} - e^{-nr}(S_r - S_s),$$

where

A_s = annual energy costs savings = \$4,104,

S_r = replacement costs of the solar system, and

S_s = salvage value of the initial system.

The replacement costs of the initial solar system 20 years hence would be

$$S_r = C_1 (1+ r_i)^{20},$$

where

C_1 = initial cost.

Of the \$25,101.50 expended for the solar system, \$3,398.80 went toward stronger roof trusses and additional insulation. Since these two items would not normally need replacing at the end of 20 years, their costs can be deducted from the total original cost of the solar system. Accordingly, the replacement costs 20 years hence would be

$$S_r = 21{,}701.70\ (1 + 0.05)^{20} = \$57{,}583.72.$$

The salvage value, S_s, 20 years hence is assumed to be equal to the \$21,701.70 initial cost of the replaceable components. Accordingly, the present value of the savings resulting from the initial investment of \$25,102 is \$57,347 based on the values listed above. This would result in a payback period of 10.7 years for the initial investment of \$25,101.50.

As noted earlier, the above analysis assumed the doubling of the annual fuel cost savings to account for the savings of irreplaceable fossil fuels. If only the direct electrical power cost savings are used for the present value analysis, the results are less favorable. In this case, the annual energy cost savings, A_s, of \$2,052 is used and the present value of the initial investment of \$25,102 is \$27,047. The payback period in this instance would be 19 years. Therefore, even if the annual fuel cost saving is not doubled, the investment in the active solar energy system is still slightly favorable based on the assumptions upon which the analysis is based. One can thus conclude that the use of solar energy to assist in heating the maintenance area headquarters building is a worthwhile investment.

MAINTENANCE COSTS

The maintenance cost incurred for the solar system during the course of the monitoring period was reported to the writer as being $80. This cost resulted from plumbing work required on the system.

CONCLUSIONS

1. The use of solar energy to assist in heating the maintenance area headquarters building described in this report is a favorable means of saving both energy and dollars. An evaluation of the data indicated that 74,282 kWh of power were saved over a 15-month monitoring period. On an annual basis, 53,023 kWh of power were saved. At the cost of $0.0387 per kWh being charged when the study began, this was equivalent to a $2,052 savings. At the cost of $0.049 per kWh presently being charged at the facility, future dollar savings will likely be greater.

2. If a service life of 20 years is assumed for the solar system and an interest rate of 12% per annum is used, a present value of $57,347 is obtained from the initial investment of $25,102. The payback period on the initial investment would be 10.7 years. These values are based on the assumption that the power costs savings can be doubled to account for the savings of irreplaceable fossil fuels. If only the direct electrical power costs savings are recognized, a present value of $27,047 with a payback period of 19 years would be realized. In either case, the investment in an active solar energy system to assist in heating the building and the domestic hot water is favorable. It should be noted, however, that the investment is marginal if only the direct power cost savings are assumed.

3. All of the energy required by the domestic hot water system was supplied by the solar system as designed. It should be noted, however, that the solar collector area was designed primarily to provide energy for heating space.

4. As would be expected, the majority of the energy demand by the building during the six warmer months of the year was by the domestic hot water system. The water heater consumed slightly more energy during the June through October period than during the rest of the year, which indicated a greater use of hot water by the maintenance workers during the summer.

5. The data clearly show that the solar collector area is much greater than that needed to supply energy for the domestic

hot water system alone during the warmer months. Accordingly, much of the investment in the solar system cannot be profitably used for approximately half of the year.

6. Since the water heater uses solar energy during the full year, it is this aspect of the system that renders the total system economically favorable.

7. The equivalent of 13% of the free energy from the sun was consumed by the circulation pumps during the course of the study. Had there been some use for the total energy-collecting capacity of the the system during the warmer months, however, this percentage would likely have been lower.

RECOMMENDATIONS

1. The use of active solar systems to assist in heating space and water in new highway maintenance area headquarters buildings can save energy and dollars and should be given consideration when these buildings are planned. If the saving of irreplaceable fossil fuels is the overriding consideration when contemplating the use of an active solar system this option is very favorable. If, however, only the direct power cost savings are considered, the use of an active solar system such as the one evaluated, having a 19-year payback on a 20-year estimated service life, is marginally favorable.

2. Domestic water heaters can make use of available solar energy all year. The results of this study suggest that solar energy should be considered for heating water for use in all office facilities wherever feasible.

ACKNOWLEDGEMENTS

Thanks are extended to B. W. Sumpter, then assistant district engineer in Lynchburg and now district engineer in Salem, and E. M. Mitchell, highway engineer, and Walter Eads, electrician, of the Lynchburg District for their assistance in conducting the study. The solar installation was developed and fabricated under the supervision of Mr. Mitchell.

The monitoring instrumentation for the study was developed and installed by Professor J. H. Aylor of the University of Virginia. The computer programming used for the storage, retrieval, and reporting of the daily and monthly data was developed by Jerry Korf, former research scientist with the Research Council, who also played a major role in developing the study and planning the instrumentation. Jennifer Ward, programmer/analyst with the Council, processed the data and assisted Mr. Korf with the computer programming. Jimmy French, technician supervisor, assisted with the data retrieval. The author gratefully acknowledges the assistance of all these individuals.

REFERENCES

1. Solar Energy Handbook, Theory and Applications, Amtek, Inc., Chilton Book Company, Radnor, Pennsylvania, 1979.

2. Hilton, Marvin H., "The Use of Solar Energy for Heating an Asphalt Storage Tank," Report No. 85-R5, Virginia Highway & Transportation Research Council, Charlottesville, Virginia, August 1984.

APPENDIX A

DESIGN DETAILS OF THE MAINTENANCE AREA HEADQUARTERS BUILDING'S SOLAR HEATING SYSTEM

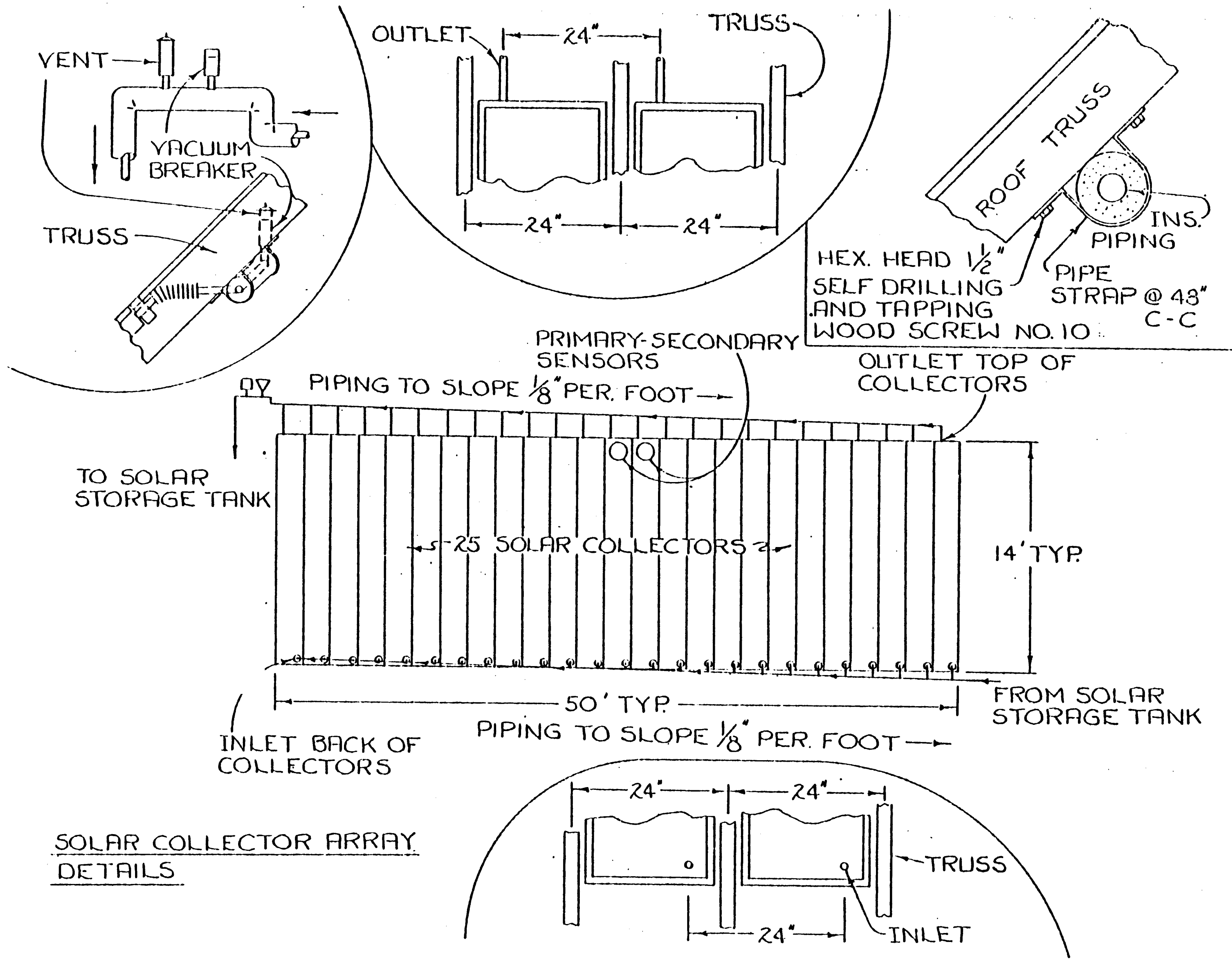


Figure A-1. Details of the solar collector array.

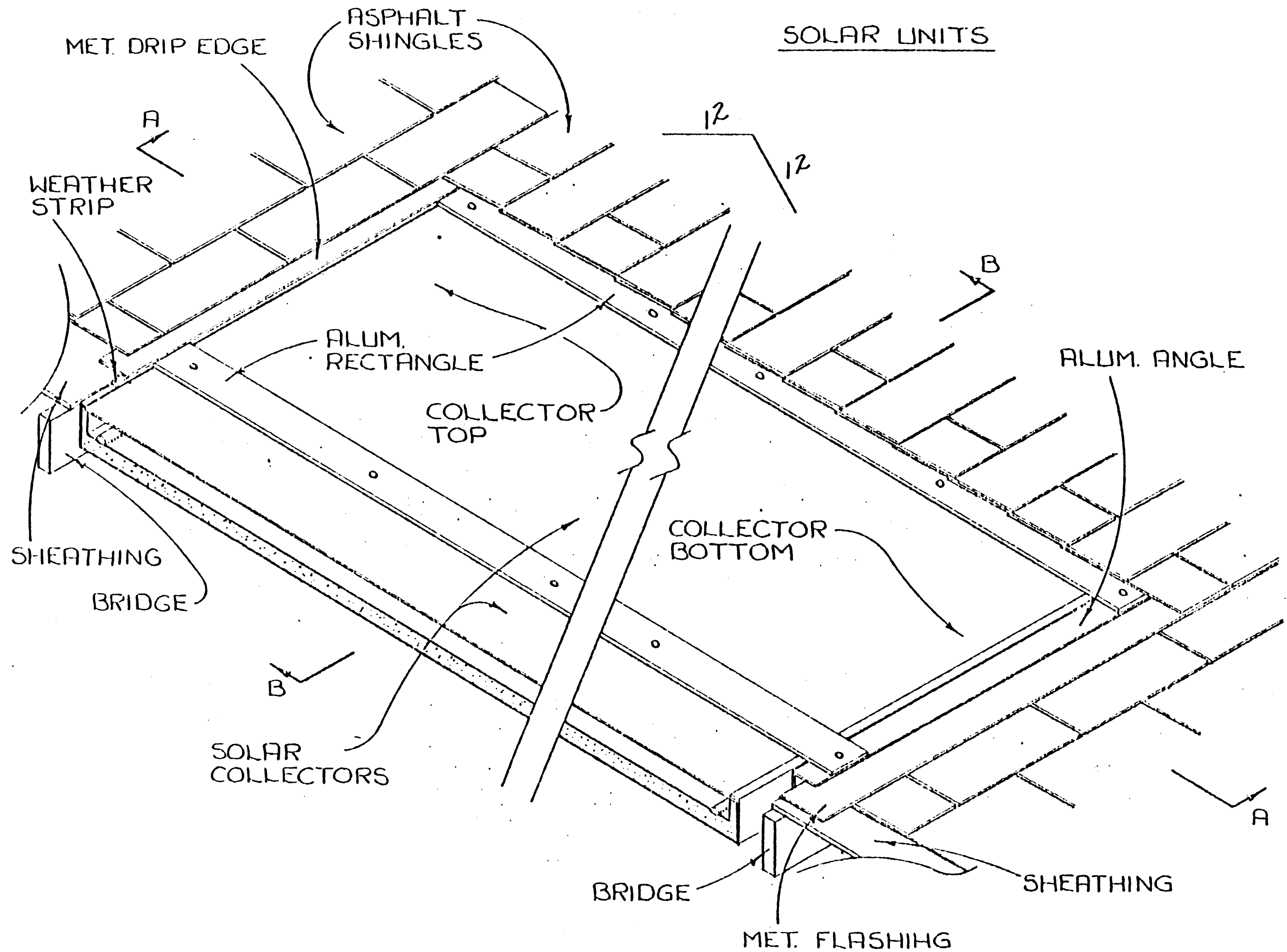


Figure A-2. Details of mounting solar collectors to roof of building.

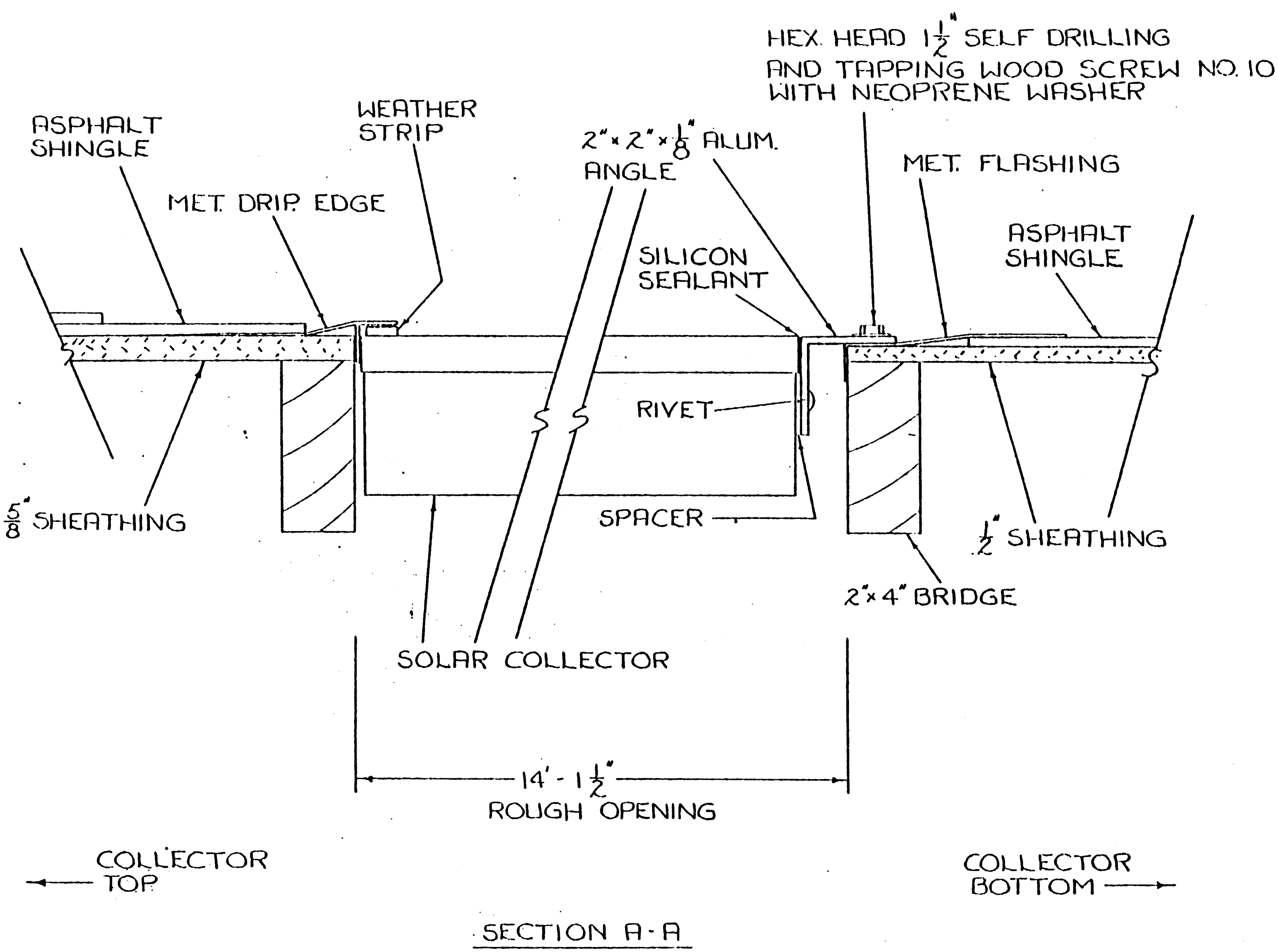


Figure A-3. Section AA from Figure A-2 showing additional details for mounting solar collectors to roof of building.

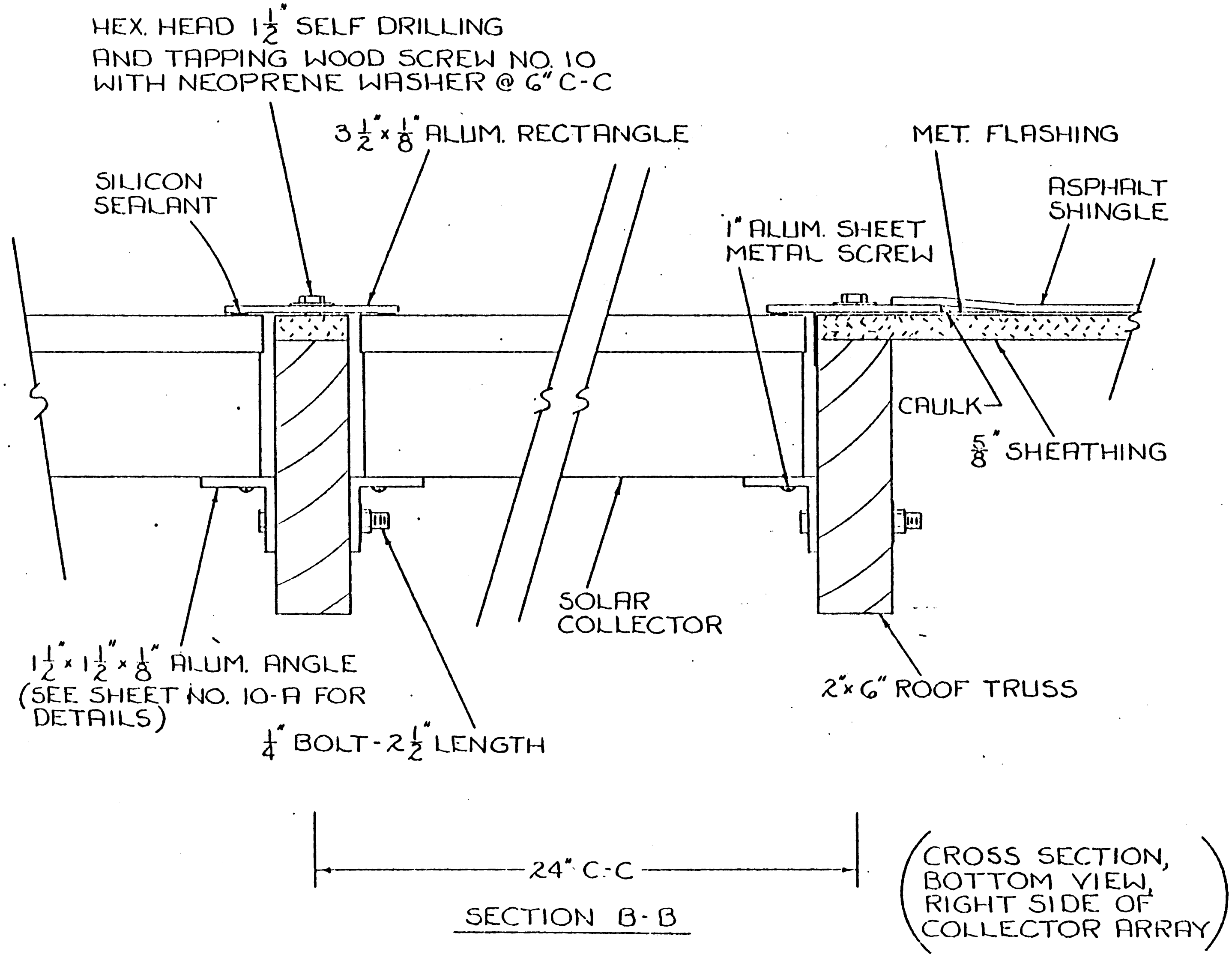


Figure A-4. Section BB from Figure A-2 showing additional details for mounting solar collectors to roof of building.

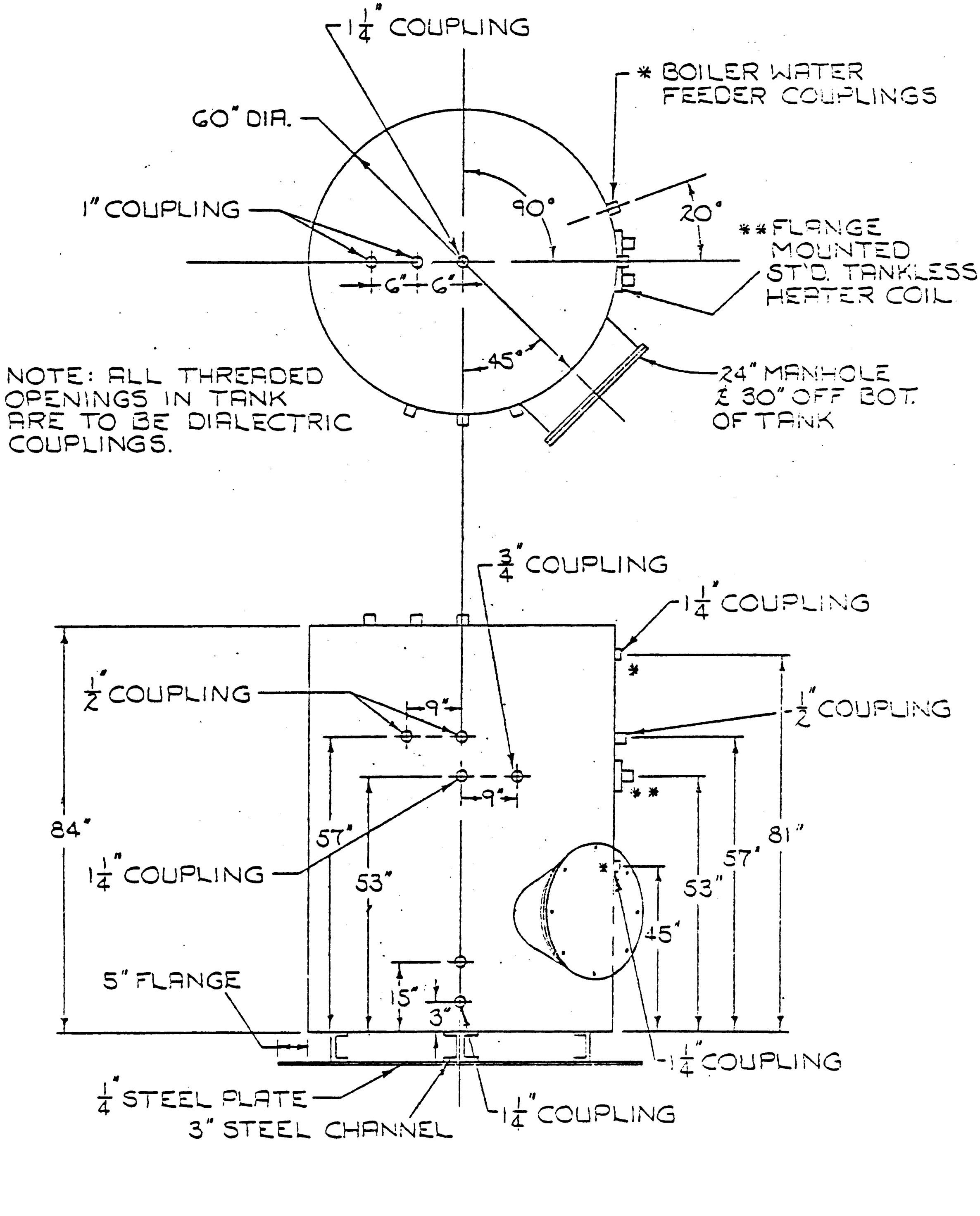


Figure A-5. Details of 1,000 gallon solar storage tank.

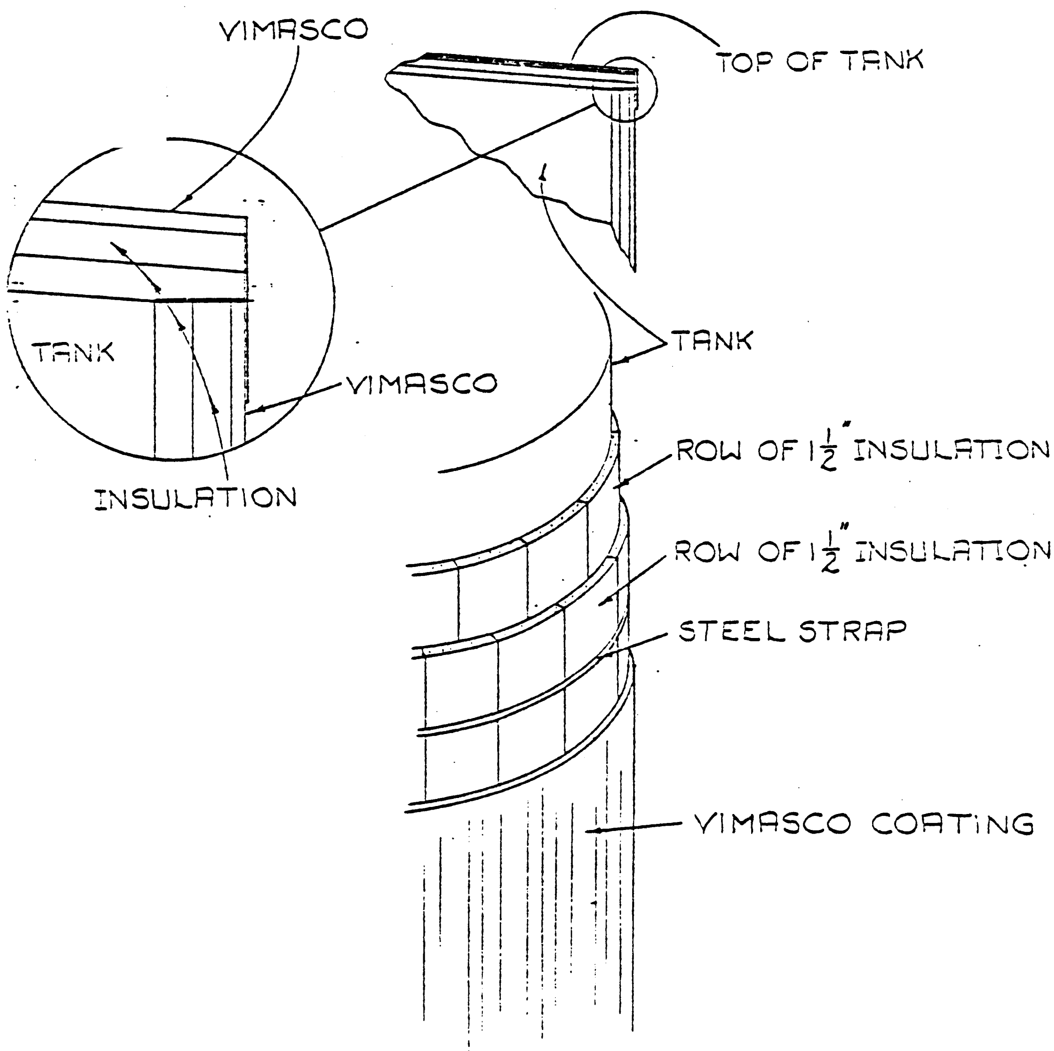
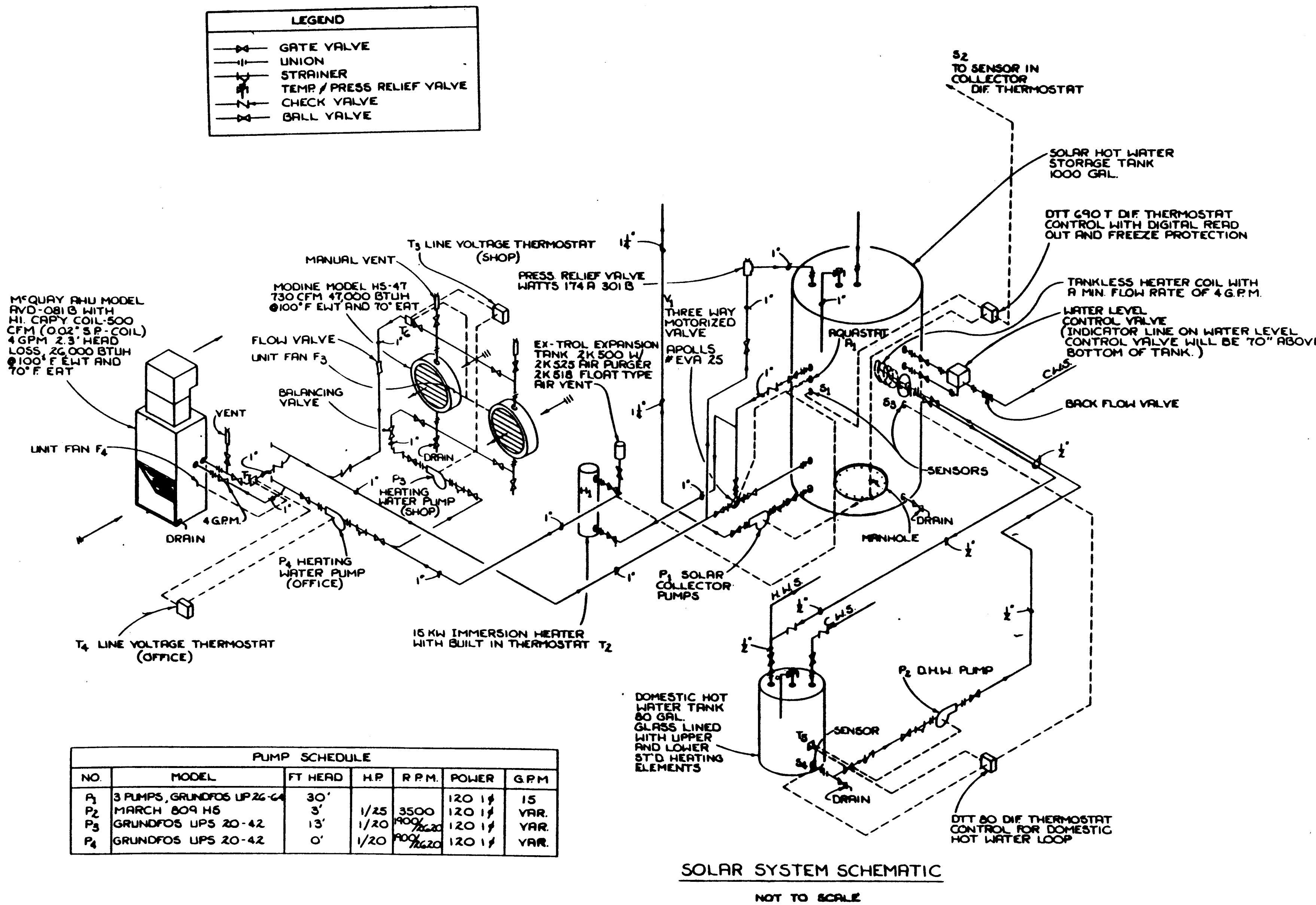


Figure A-6. Solar storage tank insulation details.



PUMP SCHEDULE

NO.	MODEL	FT HEAD	H.P.	R.P.M.	POWER	G.P.M.
P1	3 PUMPS, GRUNDFOS UP 26-64	30'			120 1ϕ	15
P2	MARCH 809 HS	3'	1/25	3500	120 1ϕ	VAR.
P3	GRUNDFOS UPS 20-42	13'	1/20	1900/2620	120 1ϕ	VAR.
P4	GRUNDFOS UPS 20-42	0'	1/20	1900/2620	120 1ϕ	VAR.

Figure A-7. Complete schematic of solar system including heating units, tanks, etc.

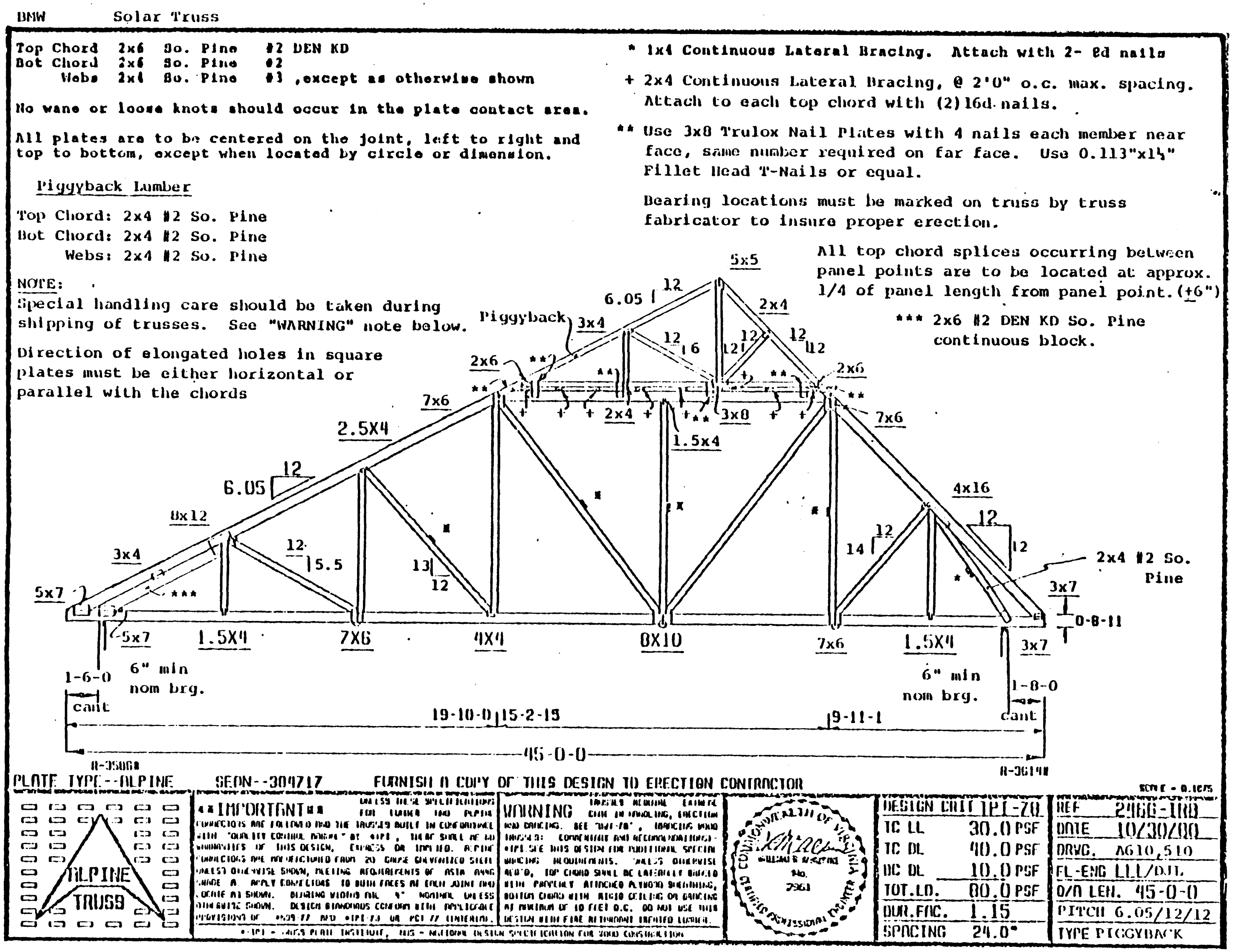


Figure A-8. Details of roof trusses.

APPENDIX B

TYPICAL MONTHLY ENERGY DATA FOR OPERATION OF SOLAR HEATED MAINTENANCE AREA HEADQUARTERS BUILDING

MONTHLY SOLAR PERFORMANCE REPORT FOR CONTRACT DOT-FH-15-371
AREA HEADQUARTERS - ROUTE 682 CAMPBELL COUNTY VIRGINIA

FEBRUARY, 1983

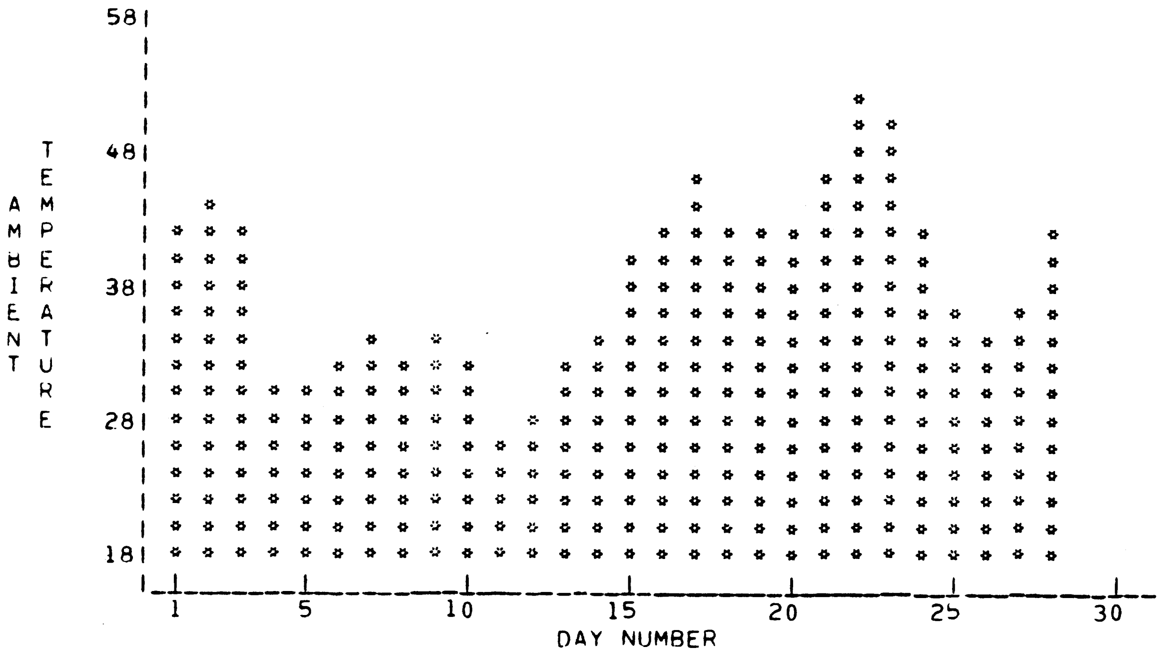


Figure B-1.

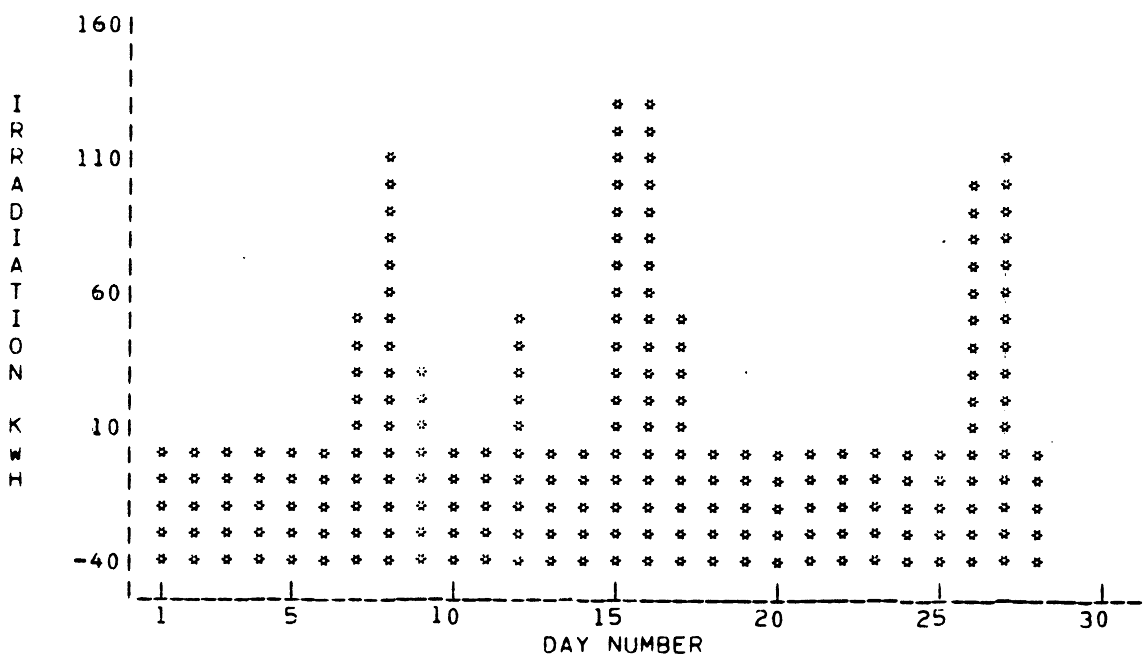


Figure B-2.

MONTHLY SOLAR PERFORMANCE REPORT FOR CONTRACT DOT-FH-15-371
AREA HEADQUARTERS - ROUTE 682 CAMPBELL COUNTY VIRGINIA

FEBRUARY, 1983

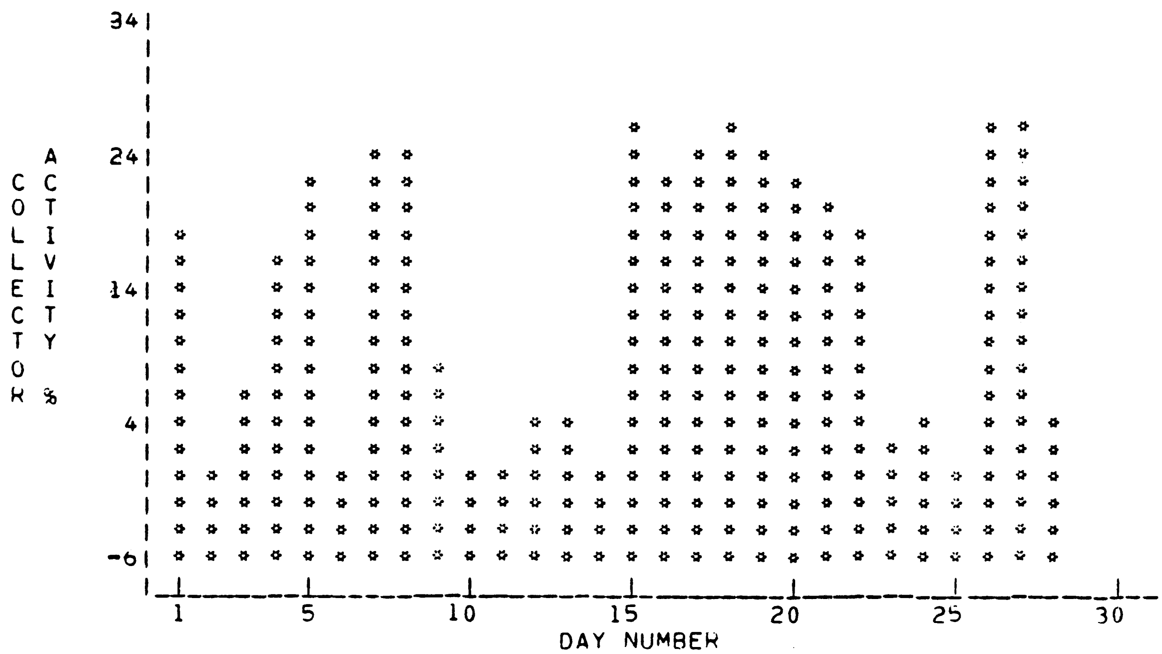


Figure B-3.

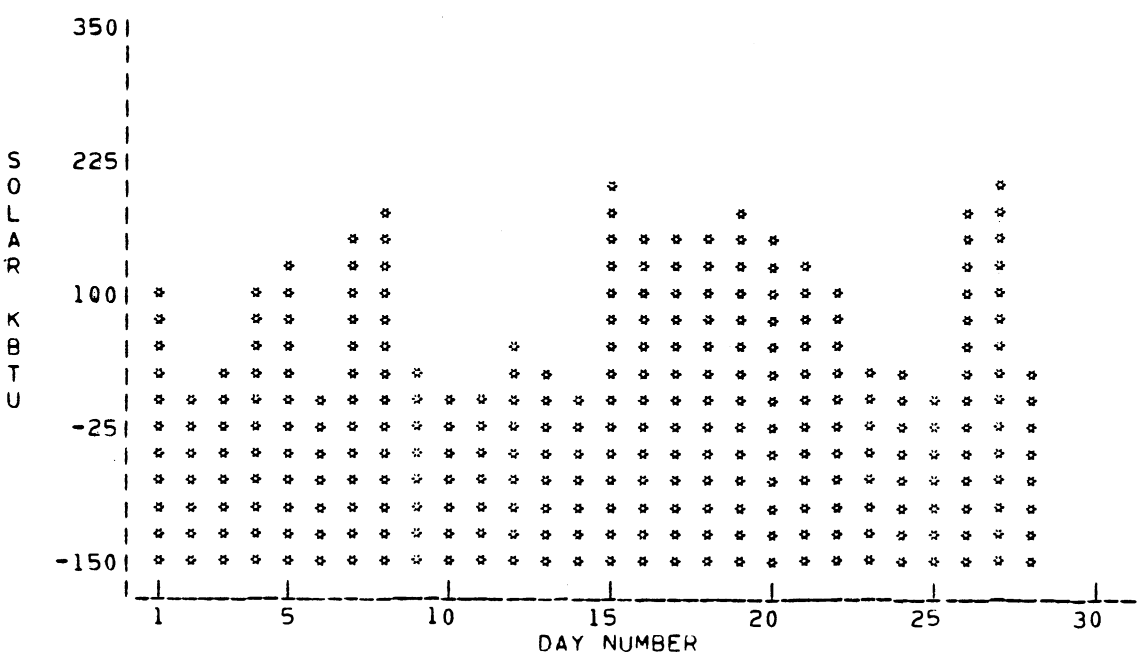


Figure B-4.

MONTHLY SOLAR PERFORMANCE REPORT FOR CONTRACT DOT-FH-15-371
AREA HEADQUARTERS - ROUTE 682 CAMPBELL COUNTY VIRGINIA

FEBRUARY, 1983

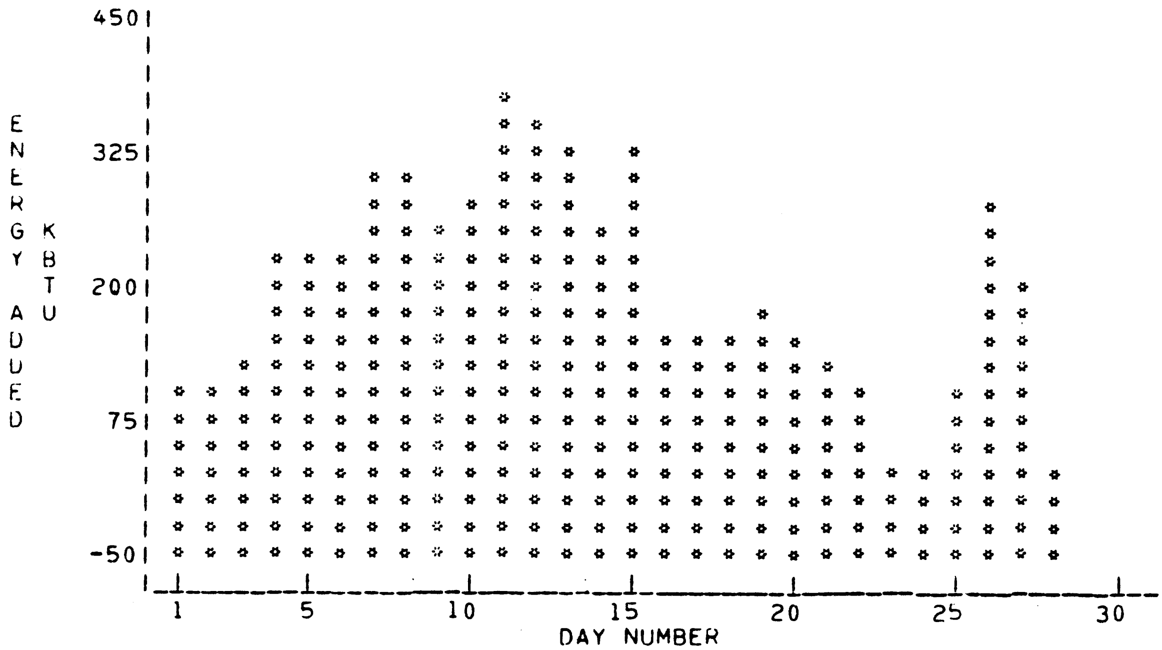


Figure B-5.

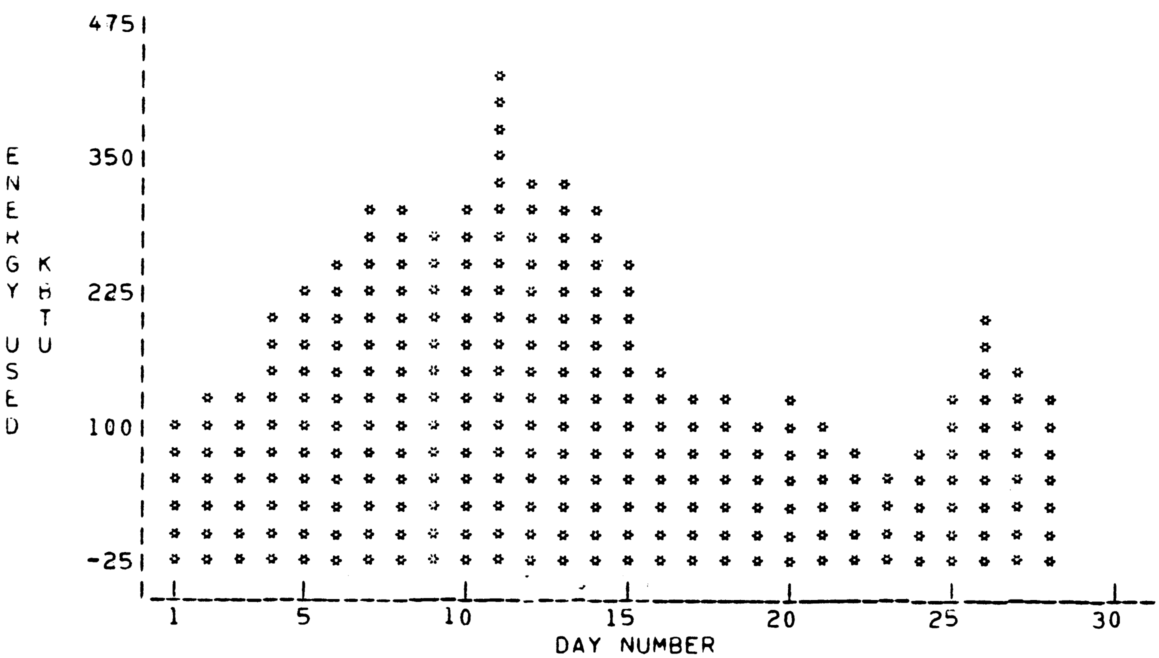


Figure B-6.

MONTHLY SOLAR PERFORMANCE REPORT FOR CONTRACT DOT-FH-15-371
AREA HEADQUARTERS - ROUTE 682 CAMPBELL COUNTY VIRGINIA

FEBRUARY, 1983

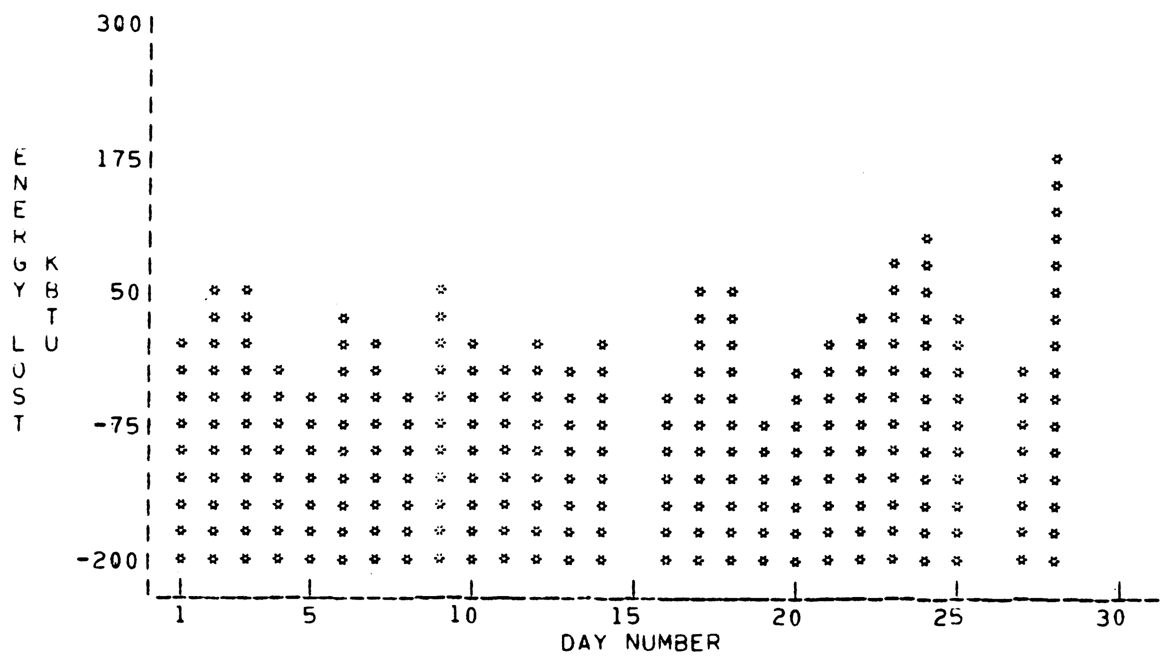


Figure B-7.

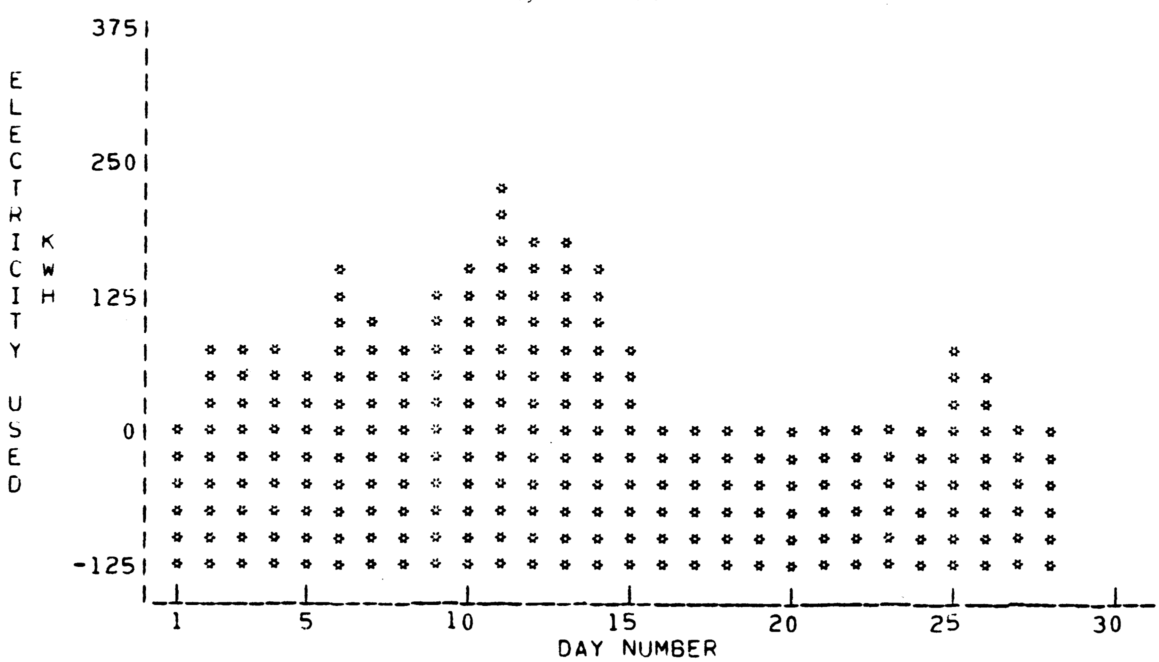


Figure B-8.

MONTHLY SOLAR PERFORMANCE REPORT FOR CONTRACT DOT-FH-15-371
AREA HEADQUARTERS - ROUTE 682 CAMPBELL COUNTY VIRGINIA

FEBRUARY, 1983

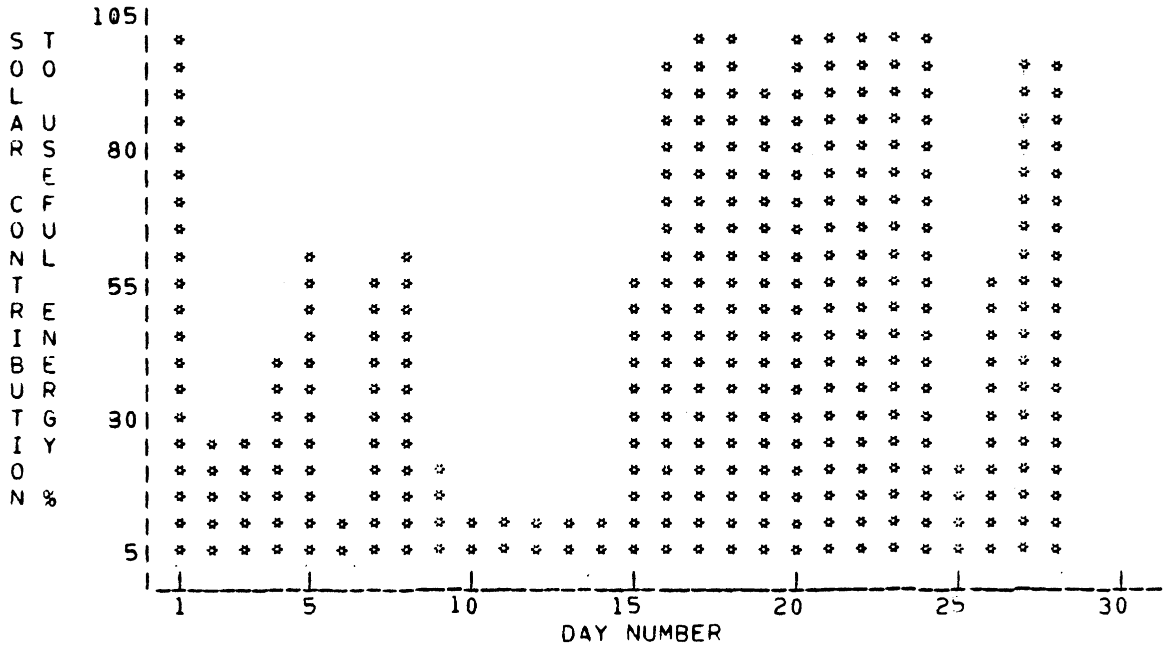


Figure B-9.