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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR SEMCO, LOXAHATCHEE, FLORIDA

Prepared by

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For the U. S. Department of Energy

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16. ABSTRACT

This report has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. It is one of a series of reports describing the operational and thermal performance of a variety of solar systems installed in Operational Test Sites under this program. The analysis used is based on instrumented system data monitored and collected for at least one full season of operation. The objective of the analysis is to report the long-term field performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The solar energy system was designed by Solar Engineering and Manufacturing Company (SEMCO) to supply domestic hot water for a family of four, single-family residences. The SEMCO System 80 consists of two liquid flat plate collectors, single tank, pump, controls, and transport lines.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1. FOREWORD

The Solar Energy System Performance Evaluation - Seasonal Report has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. The analysis contained in this document describes the technical performance of an Operational Test Site (OTS) functioning throughout a specified period of time which is typically one season. The objective of the analysis is to report the long-term performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The contents of this document have been divided into the following topics of discussion:

- System Description
- Performance Assessment
- Operating Energy
- Energy Savings
- Maintenance
- Summary and Conclusions

Data used for the seasonal analyses of the Operational Test Site described in this document have been collected, processed and maintained under the OTS Development Program and have provided the major inputs used to perform the long-term technical assessment.

The Seasonal Report document in conjunction with the Final Report for each Operational Test Site in the Development Program culminates the technical activities which began with the site selection and instrumentation system design in April 1976. The Final Report emphasizes the economic analysis of solar systems performance and features payback performance based on life cycle costs for the same solar system in various geographic regions. Other documents specifically related to this system are References [1], [2].*

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*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The Semco Loxahatchee Solar Energy System is located in the home of the refuge manager of the Loxahatchee National Wildlife Refuge in Palm Beach County, Florida. The system is designed to provide domestic hot water (DHW) to the one-story residence. The solar energy system is designed to supply ninety percent of the domestic hot water energy requirements for the residence. The hot water load specified as a design goal for the system is an average load of 1,125,000 Btu/month with a usage rate of 75 gallons per day, at not less than 140°F [2].

The collector array is composed of two Solar Engineering and Manufacturing Co. (SEMCO) Model FP40-7-DG flat plate solar collector panels connected in series. The collector panels are mounted facing south at a tilt angle of 36.7° from the horizontal. Water is utilized as the heat transport medium and is circulated directly from the 120 gallon hot water storage tank through the series-connected panels by a 1/20 HP pump. Gross area of the collectors is 80 square feet* and the collectors are double glazed with tempered glass.

The 120 gallon hot water storage tank is a standard direct feed solar tank and is externally insulated with two-inch thick, high-density fiberglass. Auxiliary energy, as required to maintain a selectable temperature, is provided to the hot water storage tank by a 240 volt, 4500 watt, electric resistance heating element. The system is shown schematically in Figure 2-1. The sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 (Reference [4]). The measurement symbol prefixes W, T, EP and I represent, respectively: flow rate, temperature, electric power and solar insolation. Figure 2-2 is a pictorial view of the refuge manager's home.

System control is accomplished by a proportional controller designed for application to solar energy systems. The controller operates on

* Some Semco documentation indicates gross array area may be as much as 84.22 ft^2 (i.e. panel is 10' 2-1/2" x 4' 1-1/2" instead of 10' x 4'). With MSFC verbal concurrence, 80 square feet has been used in all site analyses.

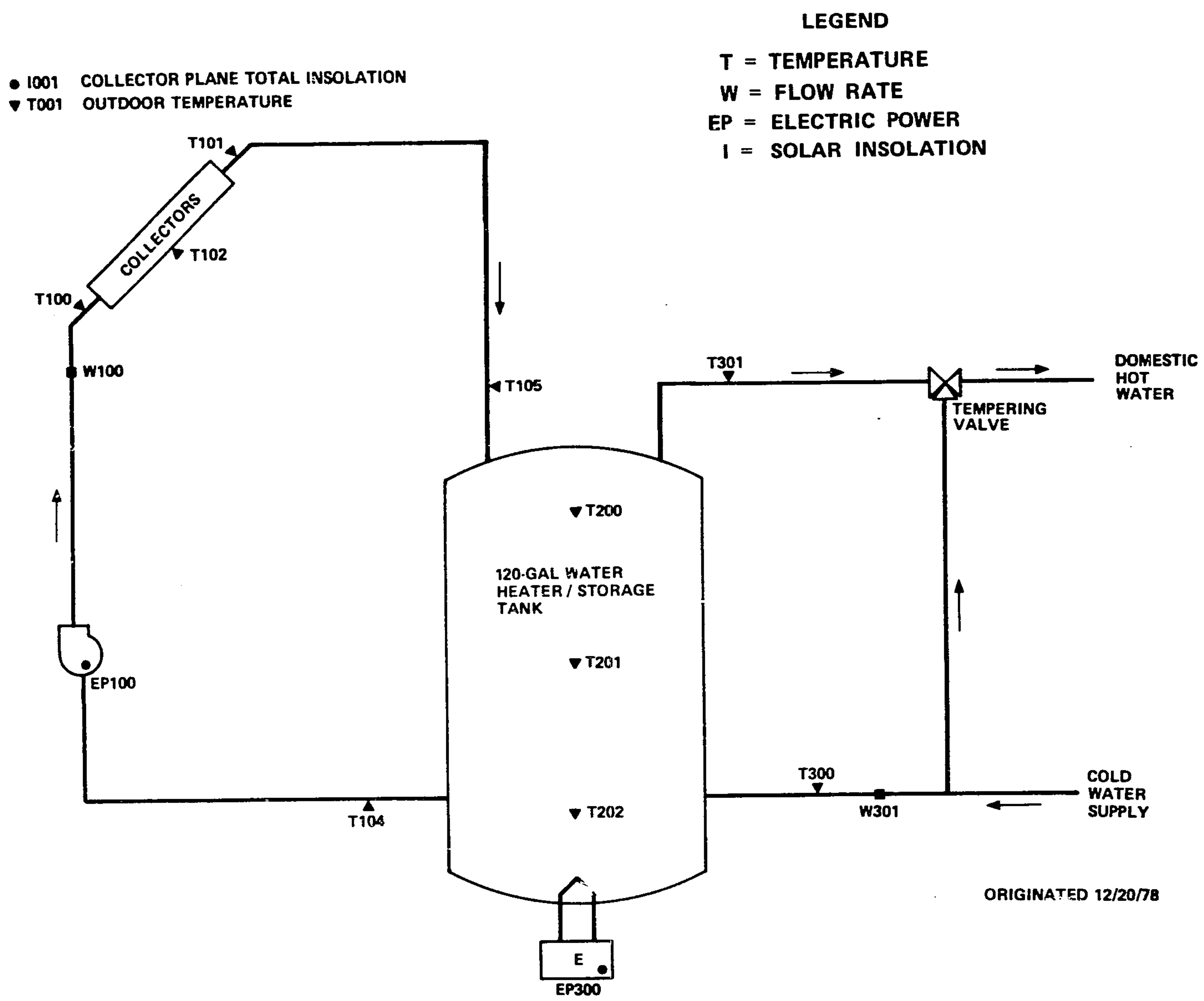
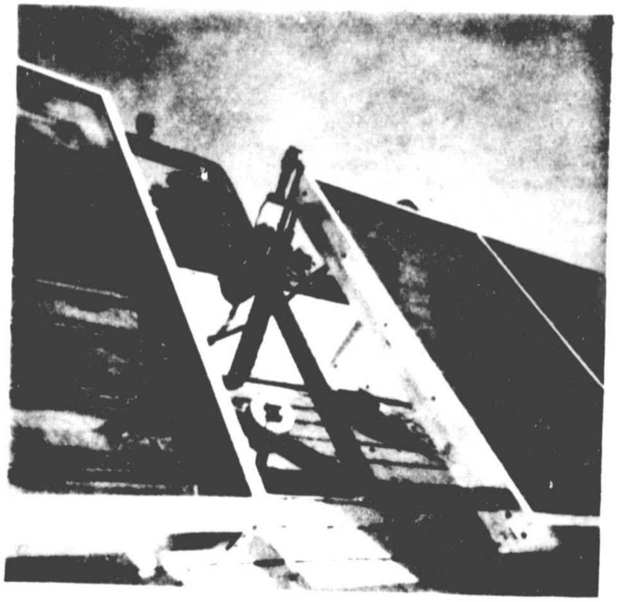
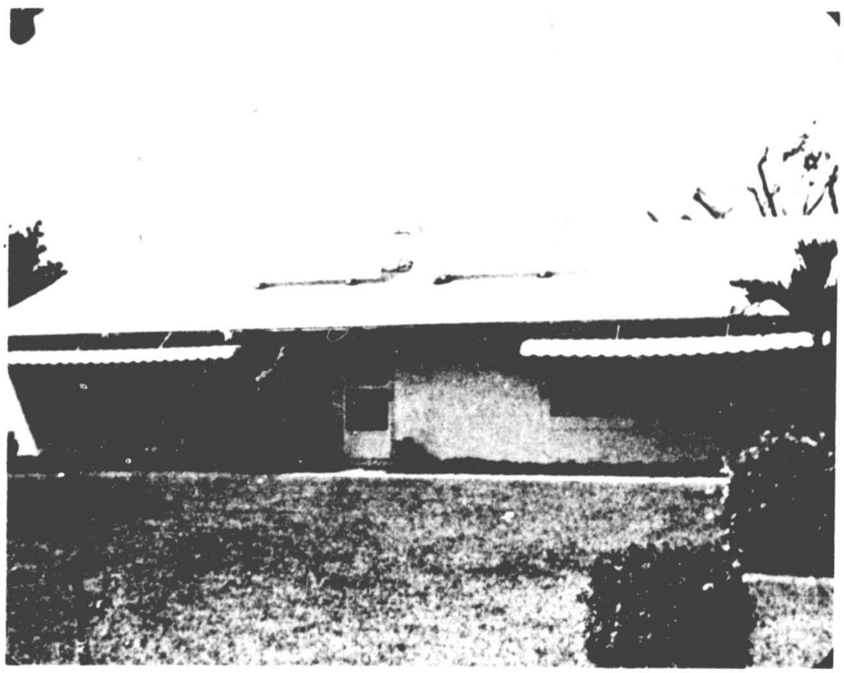


Figure 2-1 Semco Loxahatchee Solar Energy System Schematic



Semco Loxahatchee-Collector Piping Detail



Semco Loxahatchee-Ranger's Residence

Figure 2-2 Semco Loxahatchee Pictorial

a sensed difference in temperature between the collector absorber plate and the bottom of storage. The controller provides an output which controls the pump speed to produce a flow which is proportional to the collector-to-storage temperature differential over the range of 3° to 16°F; a 13°F temperature differential produces maximum pump speed and hence, maximum flow in the system.

The only active solar operational mode for the Semco Loxahatchee System is described as follows:

Mode 1 - Collector-to-Storage: This mode is entered when the differential controller recognizes that the collector absorber plate temperature exceeds the temperature in the bottom of the storage tank by a fixed value (nominally 13°F). The mode is terminated when the measured differential temperature drops below a fixed value (nominally 3°F).

The Semco Loxahatchee Solar Energy System is an application that utilizes a single domestic hot water tank. This is considered an appropriate design feature for systems where nominal daily usage is less than the capacity of the tank. This feature enables the standby losses to be made up directly by solar energy, thereby saving electrical energy.

2.1 Typical System Operation

August 10, 1979 has been selected as a day which illustrates typical operation of the Semco Loxahatchee Solar Energy System. Figure 2.1-1 (a) is a plot of solar insolation measurement, I001 for that day which shows collector loop pump turn-on at 9:25 AM when the value of solar insolation had reached 133 Btu/ft^2-hr. Collector loop operation was continuous until 4:31 PM when the collector loop pump turned off at an insolation level of 78 Btu/ft^2-hr.

Included in Figure 2.1-1(b) is a plot of the collector absorber plate temperature measurement, T102. In this plot, the 9:25 AM turn-on of the collector loop pump occurred at an absorber plate temperature of 145°F and 4:31 PM turn-off was noted when the declining absorber plate temperature had reached 163°F. At the time of collector pump turn-off, temperature, T202 at the bottom of the storage tank was approximately 164°F. It is to be noted that T102 and T202 are not the temperature sensors used by the control system but are representative of the temperature conditions seen by the corresponding control sensors.

Figure 2.1-1 (c) and (d) are plots of collector inlet temperature, T100 and collector outlet temperature, T101, respectively during the collector loop operating period. Corresponding to the turn-on times indicated in Figure 2.1-1 (a) when collector loop flow was established, collector inlet temperature was approximately 139°F and collector outlet temperature was 141°F. At the time of collector loop turn-off, collector inlet temperature was approximately 164°F and the collector outlet temperature was 163°F.

On the day chosen to illustrate typical system operation, the system was controlled in a manner consistent with design criteria. On this date, the incident solar energy was 135,000 Btu of which 43,000 Btu were collected thus demonstrating a collector array efficiency of 32%. Of the 43,000 Btu collected, 16,000 Btu were supplied to the hot water load. The ratio of solar energy supplied to the hot water subsystem to solar energy collected, on this date, was 0.37.

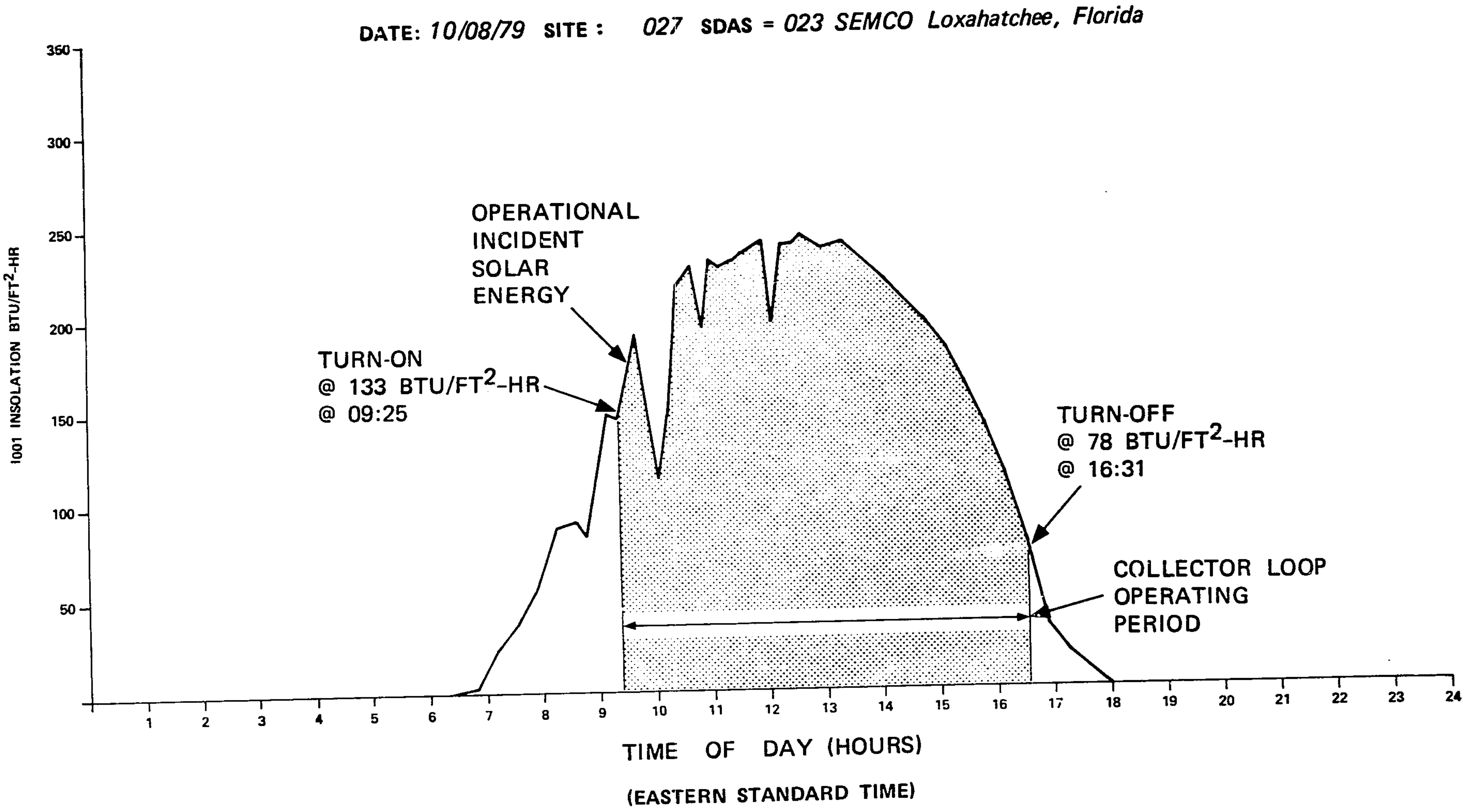


Figure 2.1-1(a) Solar Insolation Vs. Time of Day

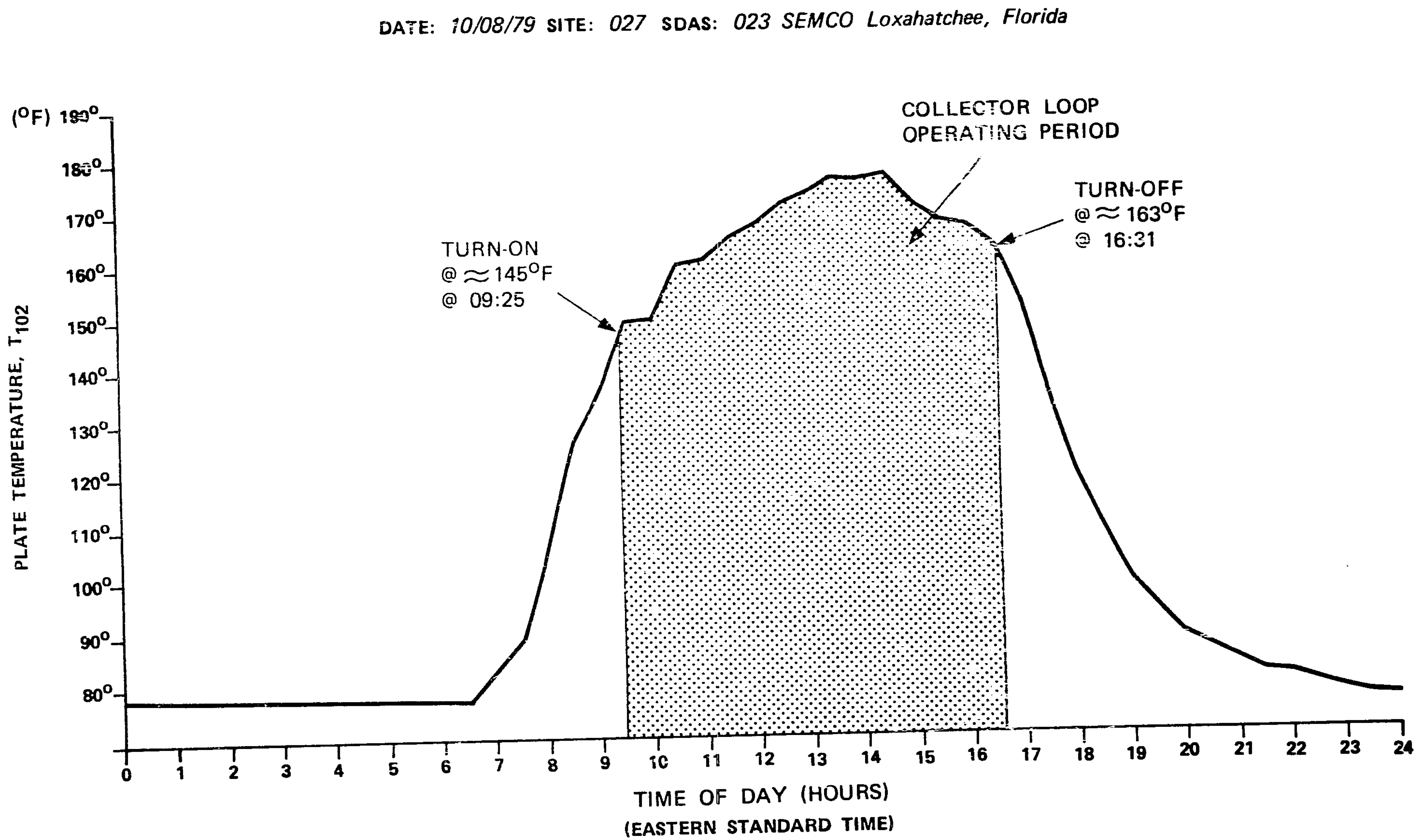


Figure 2.1-1(b) Absorber Plate Temperature Vs. Time of Day

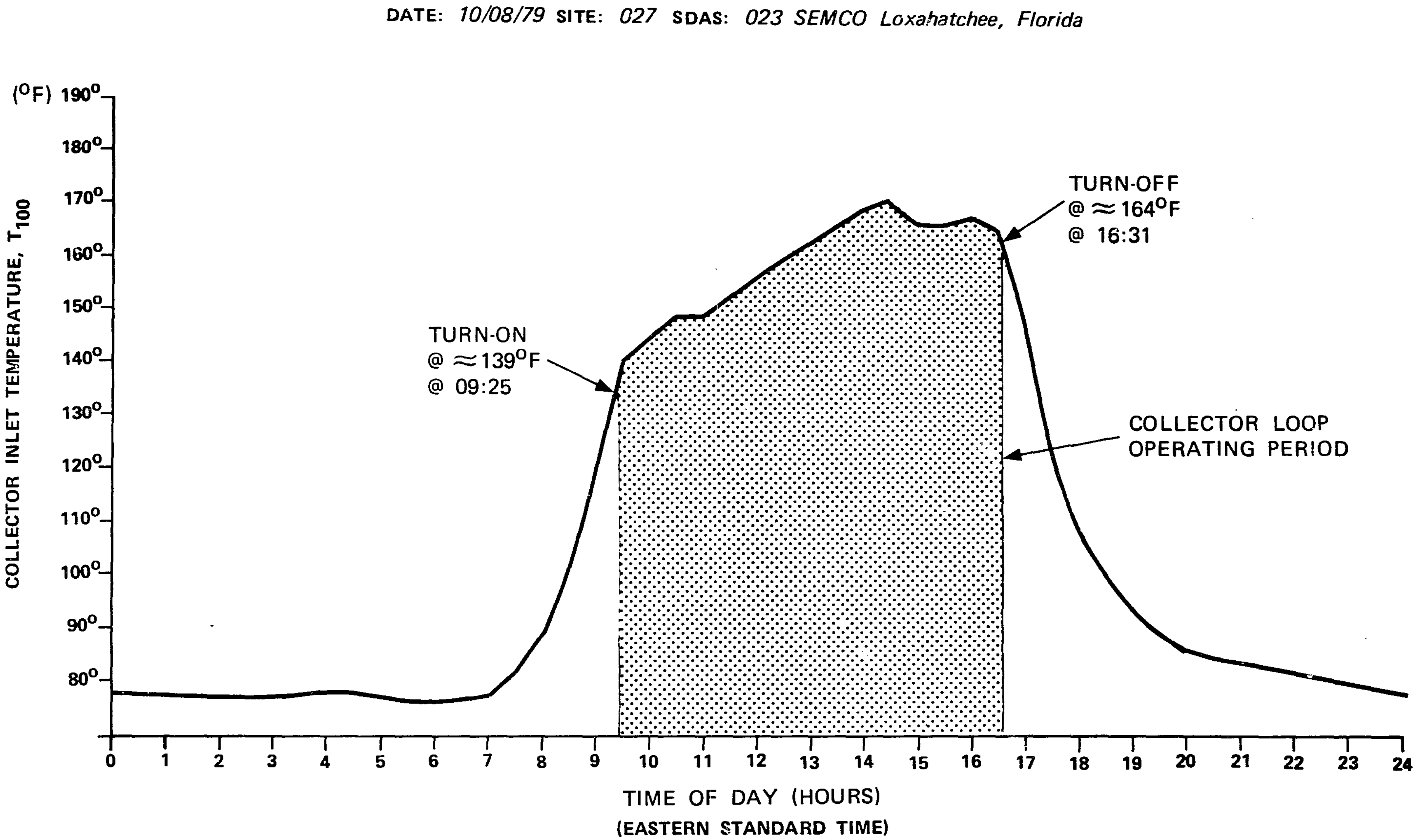


Figure 2.1-1(c) Collector Inlet Temperature Vs. Time of Day

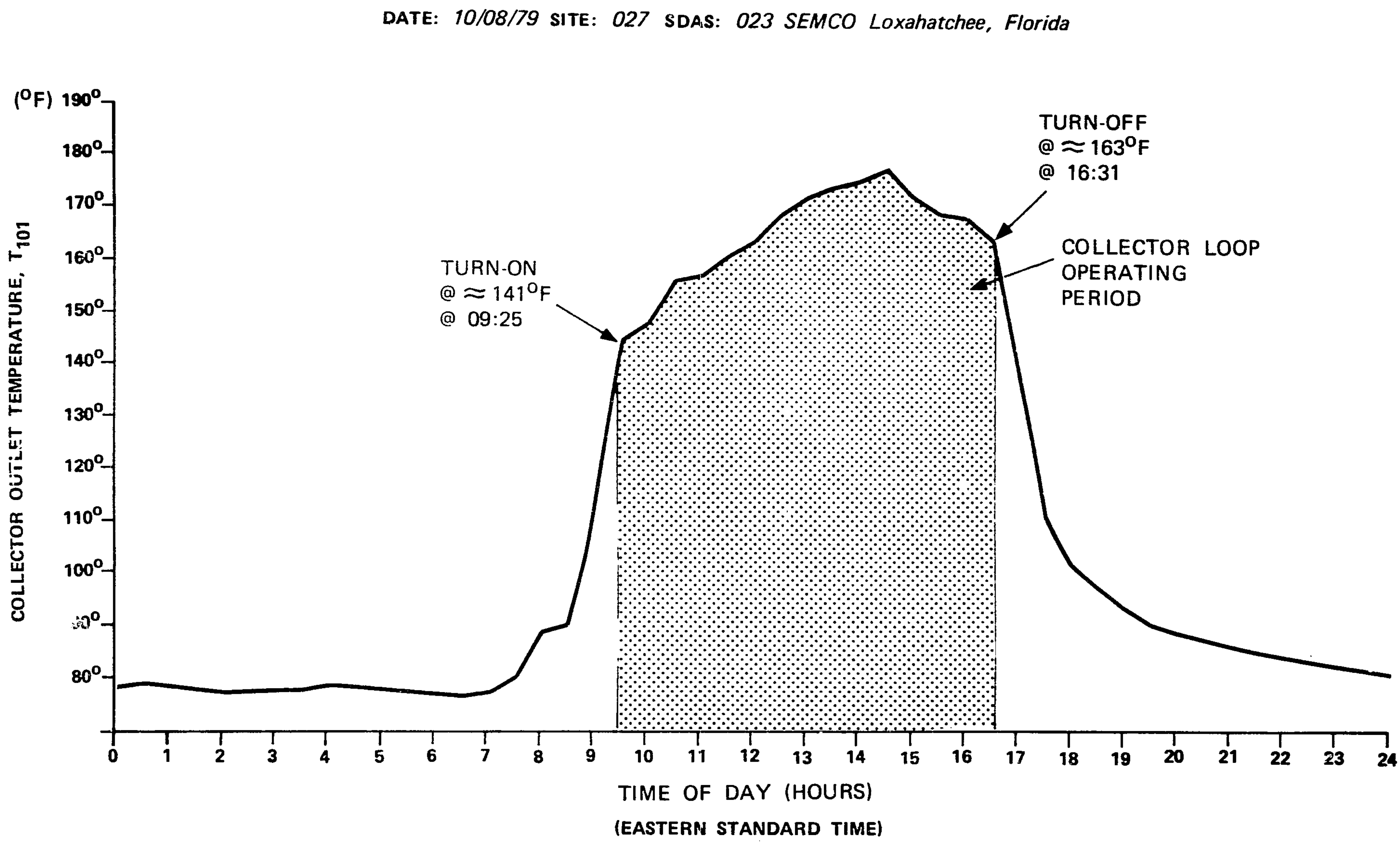


Figure 2.1-1(d) Collector Outlet Temperature Vs. Time of Day

2.2 System Operating Sequence

For August 10, 1979, the day selected for discussion of typical solar energy system operation, the operating sequence of the Semco Loxahatchee system is charted in Figure 2.2-1. As shown by the figure, solar DHW heating, storage charging and collector loop operation are simultaneous due to the one-tank design of the system. During the ECSS operational period, solar energy satisfied all of the energy demands on the hot water system due to domestic hot water usage which was approximately 26 gallons. Additionally, solar energy replenished all of the thermal energy losses of the storage tank during this period, such that no auxiliary heating was required. Of the total of 40,000 Btu of solar energy supplied to the hot water tank, 16,000 Btu were supplied to the hot water load and the balance of 24,000 Btu were required to supply thermal losses from the storage tank.

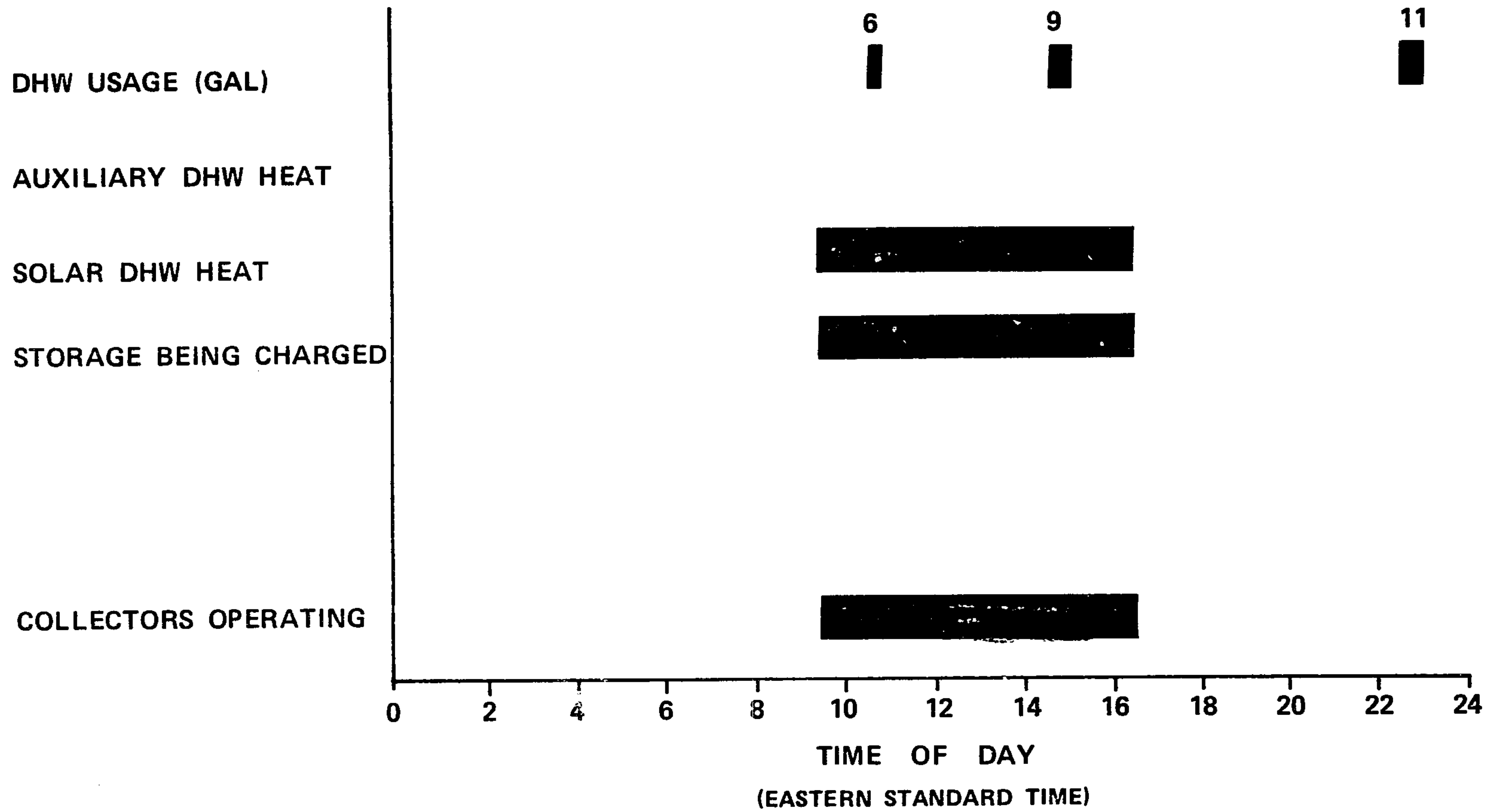


Figure 2.2-1 Operating Sequence - August 10, 1979

3. PERFORMANCE ASSESSMENT

The performance of the Semco Loxahatchee Solar Energy System has been evaluated for the October 1978 through August 1979 time period from two perspectives. The first was the overall system view in which the performance values of system solar fraction and net energy savings were evaluated against the prevailing and long term average climatic conditions and system loads. The second view presents a more in depth look at the performance of the individual subsystems. Details relating to the performance of the system are presented first in Section 3.1 followed by the subsystem assessment in Section 3.2.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the Semco Loxahatchee Solar Energy System located in Palm Beach County, Florida. This analysis was conducted by evaluation of measured system performance against the comparison of measured climatic data with long-term average climatic conditions. The performance of the system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report, "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [4]. The performance of the major subsystems is also evaluated in subsequent sections of this report.

The measurement data were collected for the period October 1978 through August 1979. System performance data were provided through an IBM developed Central Data Processing System (CDPS) [3] consisting of a remote Site Data Acquisition System (SDAS), telephone data transmission lines and couplers, an IBM System 7 computer for data management, and an IBM System 370/145 computer for data processing. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. These data are processed daily and summarized into monthly performance formats which form a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data contained in this report.

The solar energy system performance summarized in this section can be viewed as the dependent response of the system to certain primary inputs. This relationship is illustrated in Figure 3.1-1. The primary inputs are the incident solar energy, the outdoor ambient temperature and the system load. The dependent responses of the system are the system solar fraction and the total energy savings. Both the input and output definitions are as follows:

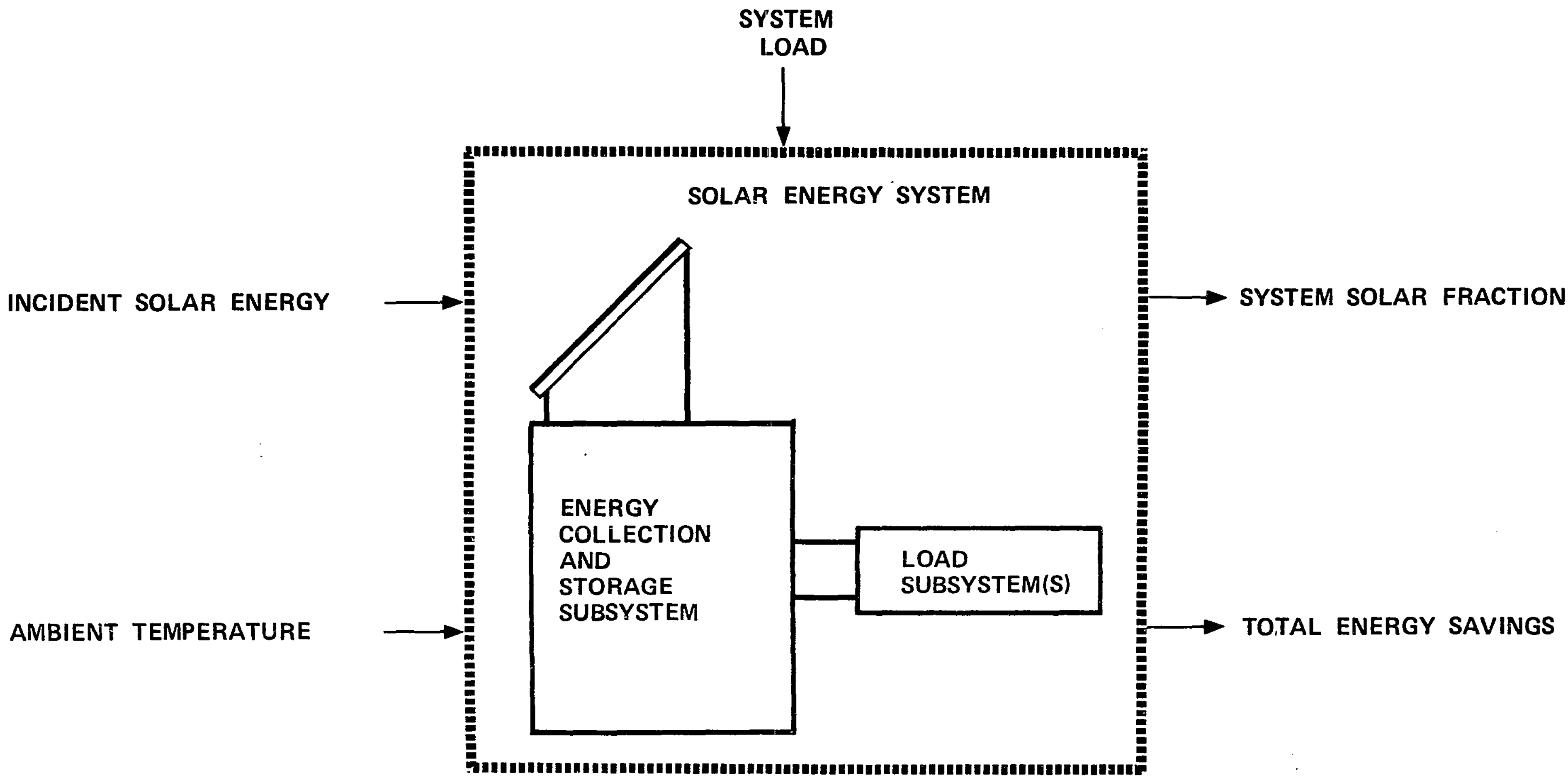


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

- Incident solar energy - The total solar energy incident on the collector array available for collection.

- Ambient temperature - The temperature of the external environment which affects both the energy that can be collected and the energy demand.

- System load - The loads that the system is designed to meet, which are affected by the life style of the user (space heating/cooling, domestic hot water, etc., as applicable).

Outputs

- System solar fraction - The ratio of solar energy applied to the system loads to total energy (solar plus auxiliary energy) required by the loads.

- Total energy savings - The quantity of auxiliary energy (electrical or fossil) displaced by solar energy.

The monthly values of the inputs and outputs for the total operational period are shown in Table 3.1-1, the System Performance Summary. Comparative long term average values of daily incident solar energy, and outdoor ambient temperature are given for reference purpose. The long term data are taken from Reference 1 of Appendix C. Generally the solar energy system is designed to supply an amount of energy that results in a desired value of system solar fraction while operating under climatic conditions that are defined by the long term average value of daily incident solar energy and

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY

SEMCO LOXAHATCHEE

Month	Daily Incident Solar Energy per Unit Area @36.7° Tilt ($Btu/ft^2 \cdot Day$)		Ambient Temperature °F		System Load-Measured	Solar Fraction (Percent)		Total Energy Savings
	Measured	Long Term Average	Measured	Long Term Average	(Million Btu)	Measured	Expected	(Million Btu)
Oct 78	1297	1506	76	78	0.18	45	49	0.42
Nov 78	1805	1497	72	72	0.05	62	68	0.50
Dec 78	1319	1451	70	68	0.07	93	71	0.73
Jan 79	1384	1451	64	67	0.05	93	69	0.69
Feb 79	1678	1606	64	67	0.01	100	87	0.69
Mar 79	1645	1729	68	71	0.00	98	87	0.82
Apr 79	(1731)[1]	1731	(75)[1]	75	(0.63)[2]	89	74	0.71
May 79	(1551)[1]	1551	(78)[1]	78	(0.63)[2]	89	69	0.71
Jun 79	1278	1380	80	81	0.66	85	59	0.88
Jul 79	1264	1454	82	82	0.68	90	60	0.91
Aug 79	1204	1470	80	83	0.56	91	61	0.81
Total	--	--	--	--	3.52	--	--	7.87
Average	1469	1530	74	75	0.32	85	69	0.72

1. Long term data used because of insufficient measured data for the month.
2. Values are average of June, July and August because of insufficient measured data for April 1979 and May 1979.

outdoor ambient temperature. If the actual climatic conditions are close to the long term average values, there is little adverse impact on the system's ability to meet design goals. This is an important factor in evaluating system performance and is the reason the long term average values are given. The data reported in the following paragraphs are taken from Table 3.1-1.

At the Semco Loxahatchee site for the eleven month report period, the long term average daily incident solar energy in the plane of the collector was 1530 Btu/ft^2. The average daily measured value was 1469 Btu/ft^2 which is about 4 percent below the long term value. On a monthly basis, August of 1979 was the worst month with an average daily measured value of incident solar energy 18 percent below the long term average monthly value. November 1978 was the best month with an average daily measured value 21 percent above the long term average monthly value. On a long term basis it is obvious that the good and bad months average out so that the long term average performance should not be adversely influenced by small differences between measured and long term average incident solar energy.

The outdoor ambient temperature influences the operation of the solar energy system in two important ways. First the operating point of the collectors and consequently the collector efficiency or energy gain is determined by the difference in the outdoor ambient temperature and the collector inlet temperature. This will be discussed in greater detail in Section 3.2.1. Secondly the load is influenced by the outdoor ambient temperature. The long term average daily ambient temperature was 75°F for the Semco Loxahatchee site which compares very favorably with the measured value of 74°F. On a monthly basis January, February, and March were the worst months, temperaturewise, when the measured temperature was 3°F below the long term daily average. This three month period of below average temperature has a slightly adverse impact on system performance. This resulted from an increased load and a decreased solar fraction which lead to a decrease in the total net savings over what normally would have been available.

The system load was expected to vary in an inverse proportion to the average monthly ambient temperature, other factors remaining constant. For the 11 month report period, the system load at Semxo Loxahatchee fluctuated from insignificant values to values slightly more than half of the design load of 1.125 million Btu per month. This reflects the unoccupied status of the site over this period. In May 1979, an automatic, timer controlled hot water load device was installed which accounts for the higher load during the latter third of the reporting period. In assessing the performance of the Semco Loxahatchee solar energy system, operation of the site during the months of June through August 1979 should represent more typical performance because of the more realistic loads. From the data in Table 3.1-1 it can be seen that the system performed very near to the design goal of 90 percent system solar fraction by achieving an average of 88 percent for the three month period.

The system load has an important affect on the system solar fraction and the total energy savings. If the load is small and sufficient energy is available from the collectors, the system solar fraction can be expected to be large. However, the total energy savings will be less than under more nominal load conditions. This is illustrated by comparing February 1979 with July 1979. The system solar fraction for February was 100 percent with a load of 0.01 million Btu and a total net savings of 0.69 million Btu. For July the system solar fraction was only 90 percent, but the load was 0.68 million Btu and the total net savings were 0.91 million Btu or 0.22 million Btu greater than in February.

In a single tank domestic hot water system such as Semco Loxahatchee, the system load may be less than the total net energy savings. The explanation is that solar energy was delivered to the load (hot water used) and also contributed to standby energy that was lost from the hot water tank. For the total period the system load was 3.52 million Btu, but the total net savings in energy were 7.87 million Btu.

Also presented in Table 3.1-1 are the measured and expected values of system solar fraction where system solar fraction is the ratio of solar energy applied to system loads to the total energy (solar plus auxiliary) applied to the loads. The expected values have been derived from a modified f-Chart analysis which uses measured weather and subsystem loads as inputs (f-Chart is the designation of a procedure that was developed by the Solar Energy Laboratory, University of Wisconsin, Madison, for modeling and designing solar energy systems [8]). The model used in the analysis is based on manufacturers' data and other known system parameters. The basis for the model are empirical correlations developed for liquid and air solar energy systems that are presented in graphical and equation form and referred to as the f-Charts where 'f' is a designator for the system solar fraction. The output of the f-Chart procedure is the expected system solar fraction. The measured value of system solar fraction was computed from measurements obtained through the instrumentation system of the energy transfers that took place within the solar energy system. These represent the actual performance of the system installed at the site.

The measured value of system solar fraction can generally be compared with the expected value so long as the assumptions which are implicit in the f-Chart procedure reasonably apply to the system being analyzed. From Table 3.1-1 the average measured value of 85 percent solar fraction exceeds the average expected value by 31 percent. There were several factors which are listed below that contributed to this performance.

- Light domestic hot water load throughout performance period.
- Long term performance of array exceeded manufacturer's specification by 6 percent.
- Single tank configuration permitted standby losses to be made up by solar energy.

The domestic hot water load was unrealistic during the period of October through March. Only during the last three months of the 11 month performance period did the load become sufficient for confident analysis; however, the average solar fraction of 88 percent for this three month period indicates that the system performance would be good for reasonable loads.

The long term performance of the collector array was 6 percent above the manufacturer's specification primarily because the flow of the heat transfer fluid was 45 percent greater than in the manufacturer's test. Array performance is discussed in greater detail in Section 3.2.1.

The single tank domestic hot water system at the site permitted the standby losses to be made up by solar energy and is appropriate for installations having light loads. The expected performance from the f-Chart model is predicated on a two tank system where some of the standby losses must be made up by auxiliary energy even though solar energy is available. This is because energy transfer from the preheat tank to the domestic hot water tank in the two tank system takes place only when hot water is used. The two tank system is appropriate, however, for higher load applications. The single tank configuration tends to be under predicted by the f-Chart model because of the standby loss make up. This is illustrated by the average measured solar fraction of 85 percent for the 11 month performance period compared with the expected average solar fraction of 69 percent.

The total energy saving is an important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with inexpensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment for the system. In terms of the technical analysis presented in this report the net total energy savings should be a significant positive figure. The total energy savings for the Semco Loxahatchee solar energy system was 7.87 million Btu or 2306 KwH which was considerably less than the system's savings potential. Most of the energy consumed by the system went to make up standby losses. If the load had been reasonable for the entire performance period, the total net savings should have approached or even exceeded 10 million Btu.

3.2 Subsystem Performance

The Semco Loxahatchee Solar Energy Installation may be divided into three subsystems:

1. Collector array
2. Storage
3. Hot water

Each subsystem has been evaluated by the techniques defined in Section 3 and is numerically analyzed each month for the monthly performance reports. This section presents the results of integrating the monthly data available on the three subsystems for the period October 1978 through August 1979.

3.2.1 Collector Array Subsystem

The Semco Loxahatchee collector array consists of two Semco Model FP40-7-DG flat plate liquid collectors having a gross area of 80 square feet and interconnected for series flow. The flow path through each collector panel is serpentine. Interconnection and flow details, as well as other pertinent operational characteristics are shown in Figure 3.2.1-1(a) and (b). The collector subsystem analysis and data are given in the following paragraphs.

Collector array performance is described by the collector array efficiency. This is the ratio of collected solar energy to incident solar energy, a value always less than unity because of collector losses. The incident solar energy may be viewed from two perspectives. The first assumes that all available solar energy incident on the collectors be used in determining collector array efficiency. The efficiency is then expressed by the equation:

$$\eta_c = Q_s/Q_i \qquad (1)$$

where η_c = Collector array efficiency

Q_s = Collected solar energy

Q_i = Incident solar energy

The efficiency determined in this manner includes the operation of the control system. For example, solar energy can be available at the collector, but the collector absorber plate temperature may be below the minimum control temperature set point for collector loop operation, thus the energy is not collected. The monthly efficiency by this method is listed in the column entitled "Collector Array Efficiency" in Table 3.2.1-1.

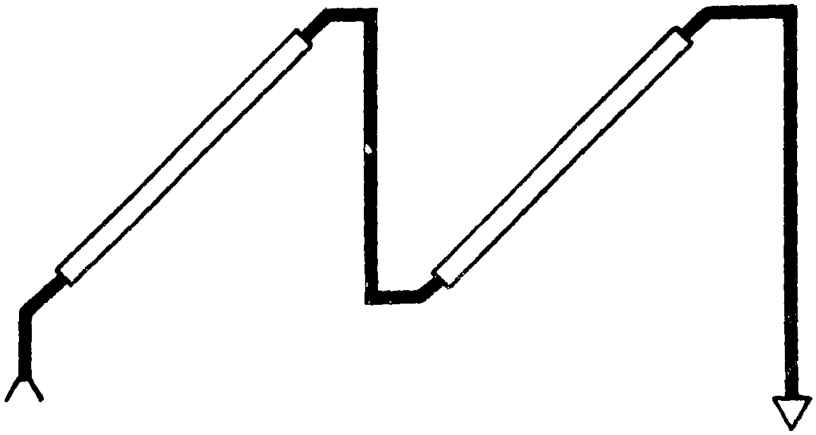


Figure 3.2.1-1(a) Collector Array Arrangement (2 Single Panels)

Panel Shown Without
Four Section Cover

Figure 3.2.1-1(b) Collector Panel Liquid Flow Path (Serpentine)

Collector Data

Manufacturer - SEMCO

Model - FP40-7-DG

Type - Liquid

Number of Collectors - Two

Flow Paths - One

Site Data

Location - Loxahatchee National Wildlife Refuge, Palm Beach Co., FLA

Latitude - 26.7°N

Collector Tilt - 36.7°

Longitude - 80.3°W

Azimuth - 0°

Figure 3.2.1-1 Collector Array Schematic

TABLE 3.2.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Array Efficiency
Oct 78	3.22	1.02	0.32	2.79	0.37
Nov 78	4.33	1.40	0.32	3.93	0.36
Dec 78	3.27	0.88	0.27	2.62	0.34
Jan 79	3.43	0.88	0.26	2.77	0.32
Feb 79	3.76	0.89	0.24	3.16	0.28
Mar 79	4.08	1.02	0.25	3.43	0.30
Apr 79	(4.15)(1)	1.20	(0.29)(1)	(3.53)(1)	(0.34)(1)
May 79	(3.85)(1)	1.08	(0.28)(1)	(3.27)(1)	(0.33)(1)
Jun 79	3.07	0.98	0.32	2.62	0.37
Jul 79	3.14	1.02	0.32	2.72	0.38
Aug 79	2.99	0.90	0.30	2.50	0.36
Total	39.29	11.27	--	33.34	--
Average	3.57	1.02	0.29	3.03	0.34

Notes:
(1) Values in parentheses are derived from long-term data for monthly incident solar energy and an average ratio between operational incident and total incident solar energy. This derivation was necessary because of insufficient measured data for April 79 and May 79.

The second viewpoint assumes that only the solar energy incident on the collector when the collector loop is operational be used in determining the collector array efficiency. The value of the operational incident solar energy used is multiplied by the ratio of the gross collector area to the gross collector array area to compensate for the difference between the two areas caused by installation spacing. The efficiency is then expressed by the equation:

$$\eta_{co} = Q_s/(Q_{oi} \times A_p/A_a) \quad (2)$$

where η_{co} = Operational collector array efficiency

Q_s = Collected solar energy

Q_{oi} = Operational incident solar energy

A_p = Gross collector area (the product of the number of collectors and the envelope area of one collector)

A_a = Gross collector array area (total area including all mounting and connecting hardware and spacing of units)

The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency" in Table 3.2.1-1.

In the ASHRAE Standard 93-77 [5] a collector efficiency is defined in the same terminology as the operational collector array efficiency. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector array efficiency is determined from actual dynamic conditions of daily solar energy system operation in the field.

The ASHRAE Standard 93-77 definitions and methods often are adopted by collector manufacturers and independent testing laboratories in evaluating collectors. The collector evaluation performed for this report using the field data indicates that there was an insignificant difference between the laboratory single panel collector data and the collector data determined from long term field measurements. This is not always the case, and there are two primary reasons for differences when they exist:

- Test conditions are not the same as conditions in the field, nor do they represent the wide dynamic range of field operation (i.e. inlet and outlet temperature, flow rates and flow distribution of the heat transfer fluid, insolation levels, aspect angle, wind conditions, etc.)

- Collector tests are not generally conducted with units that have undergone the effects of aging (i.e. changes in the characteristics of the glazing material, collection of dust, soot, pollen or other foreign material on the glazing, deterioration of the absorber plate surface treatment, etc.)

Consequently field data collected over an extended period will generally provide an improved source of collector performance characteristics for use in long-term system performance definition.

The operational collector array efficiency data given in Table 3.2.1-1 are monthly averages based on instantaneous efficiency computations over the total performance period using all available data. For detailed collector analysis it was desirable to use a limited subset of the available data that characterized collector operation under "steady state" conditions. This subset was defined by applying the following restrictions:

(1) The measurement period was restricted to collector operation when the sun angle was within 30 degrees of the collector normal.

(2) Only measurements associated with positive energy gain from the collectors were used, i.e., outlet temperatures must have exceeded inlet temperatures.

(3) The sets of measured parameters were restricted to those where the rate of change of all parameters of interest during two regular data system intervals* was limited to a maximum of 5 percent.

Instantaneous efficiencies (η_j) computed from the "steady state" operation measurements of incident solar energy and collected solar energy by Equation (2)** were correlated with an operating point determined by the equation:

$$x_j = \frac{T_i - T_a}{I} \tag{3}$$

where x_j = Collector operating point at the j^{th} instant

T_i = Collector inlet temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

The data points (η_j, x_j) were then plotted on a graph of efficiency versus operating point and a first order curve described by the slope-intercept formula was fitted to the data through linear regression techniques. The form of this fitted efficiency curve is:

*The data system interval was 5-1/3 minutes in duration. Values of all measured parameters were continuously sampled at this rate throughout the performance period.

**The ratio A_p/A_a was assumed to be unity in this analysis.

$$\eta_j = b - mx_j \tag{4}$$

where η_j = Collector efficiency corresponding to the j^{th} instant

b = Intercept on the efficiency axis

$(-)\ m$ = Slope

x_j = Collector operating point at j^{th} instant

The relationship between the empirically determined efficiency curve and the analytically developed curve will be established in subsequent paragraphs.

The analytically developed collector efficiency curve is based on the Hottel-Whillier-Bliss equation

$$\eta = F_R \tau\alpha - F_R U_L \left(\frac{T_i - T_a}{I}\right) \tag{5}$$

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

The correspondence between equations (4) and (5) can be readily seen. Therefore by determining the slope-intercept efficiency equation from measurement data, the collector performance parameters corresponding to the laboratory single panel data can be derived according to the following set of relationships:

$$
\begin{aligned}
b &= F_R \tau\alpha \\
&\text{and} \\
m &= F_R U_L
\end{aligned}
\qquad (6)
$$

where the terms are as previously defined

The discussion of the collector array efficiency curves in subsequent paragraphs is based upon the relationships expressed by Equation (6).

In deriving the collector array efficiency curves by the linear regression technique, measurement data over the entire performance period yields higher confidence in the results than similar analysis over shorter periods. Over the longer periods the collector array is forced to operate over a wider dynamic range. This eliminates the tendency shown by some types of solar energy systems* to cluster efficiency values over a narrow range of operating points. The clustering effect tends to make the linear regression technique approach constructing a line through a single data point. The use of data from the entire performance period results in a collector array efficiency curve that is more accurate in long term solar system performance prediction. The long term curve and the curve derived from the laboratory single panel data are shown in Figure 3.2.1-2.

The two curves of Figure 3.2.1-2 do not show the significant differences that similar analysis studies on other collectors have shown. In fact, the crossover point of the two curves falls within the operating point range where most of the collector operation occurred, as can be seen from the histograms of Figure 3.2.1-3. The long term curve does show

*Single tank hot water systems show a marked tendency toward clustering because the collector inlet temperature remains relatively constant and the range of values of ambient temperature and incident solar energy during collector operation are also relatively restricted on a short term basis.

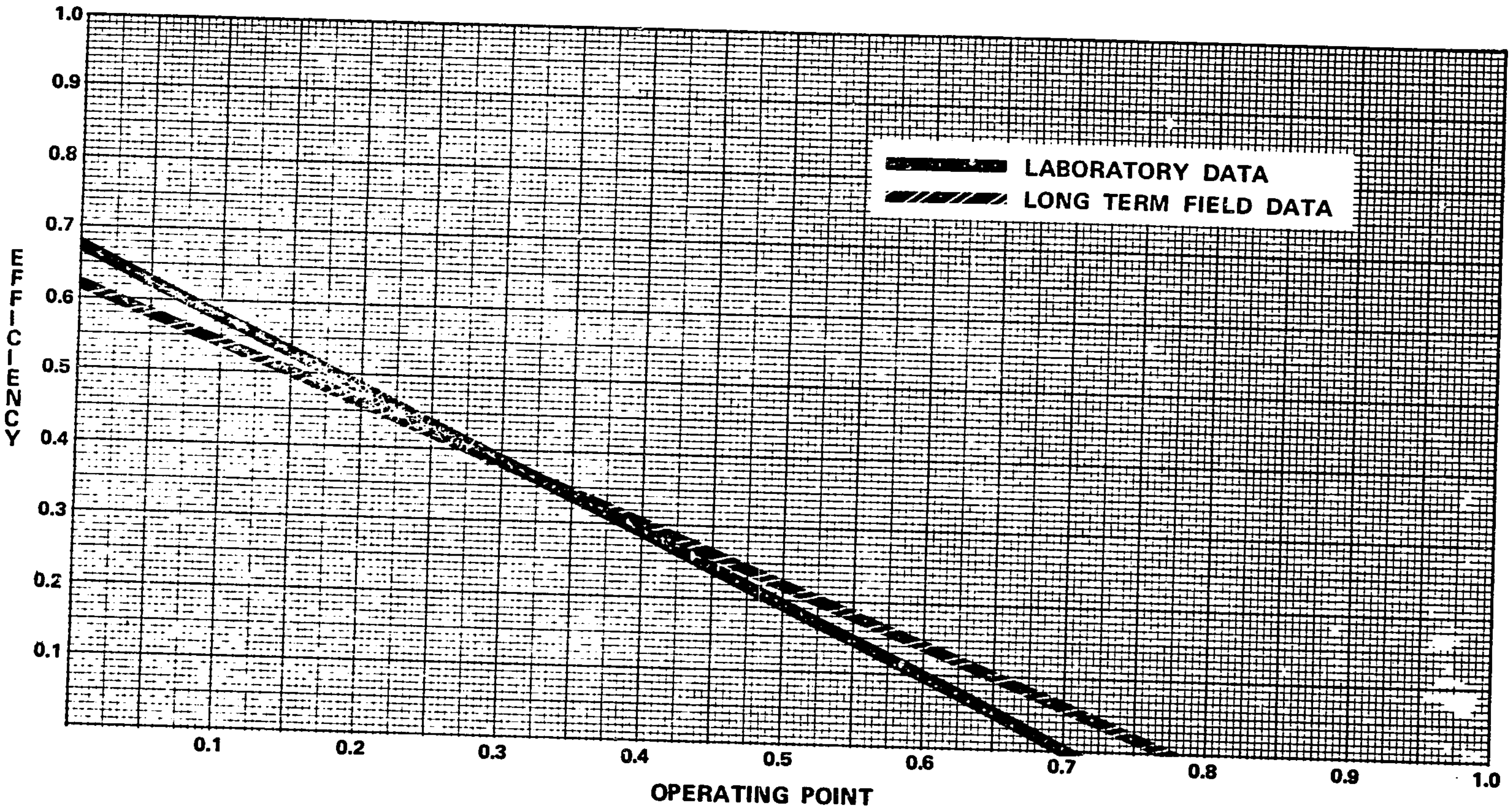


Figure 3.2.1-2 Semco Loxahatchee Collector Efficiency Curves

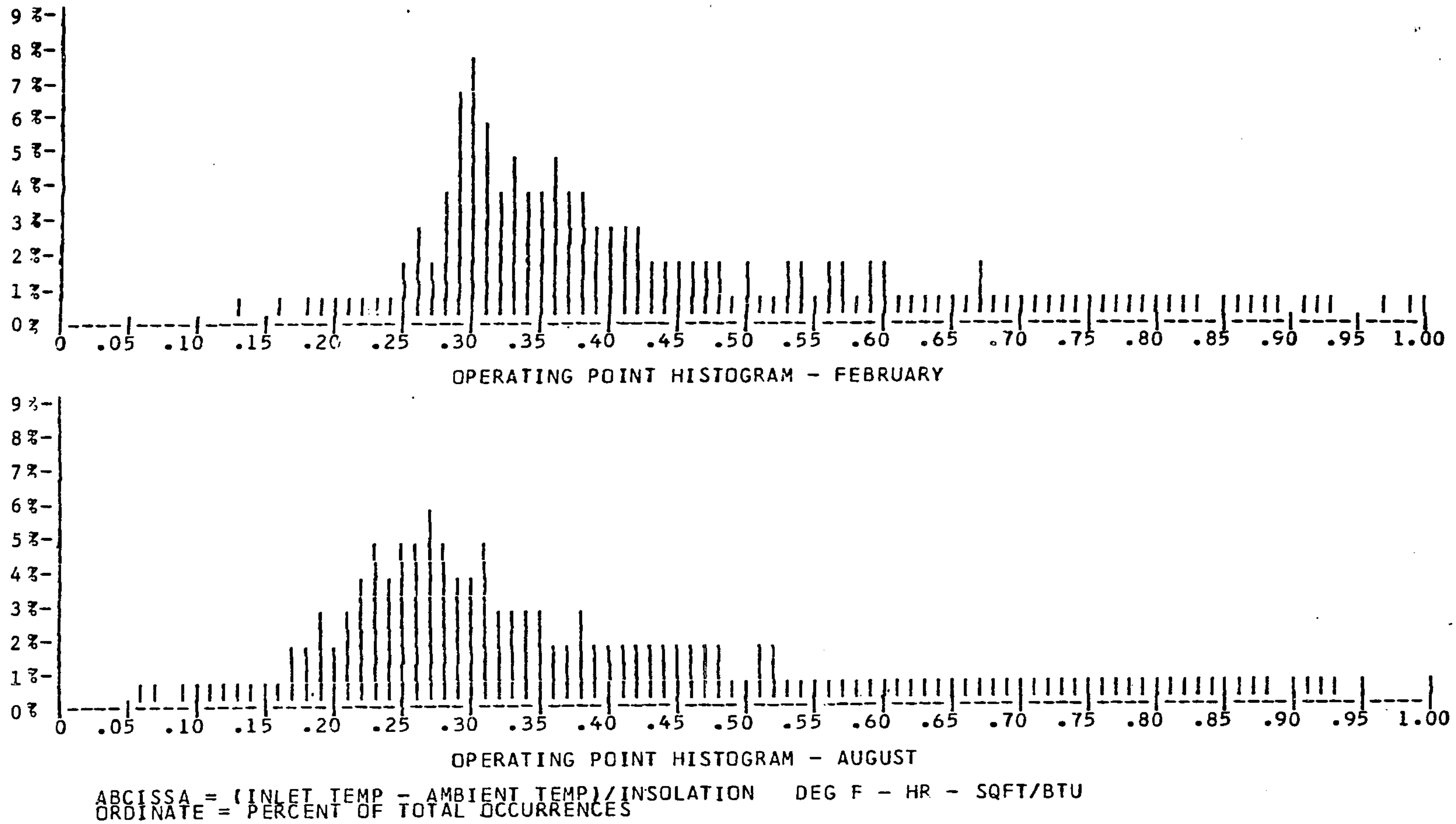


Figure 3.2.1-3

Semco-Loxahatchee Operating Point Histograms for
Typical Winter and Summer Months

a slightly less negative slope than the curve derived from single panel laboratory data. This may be attributable to the fact that the test flow rate for the single panel test was 1.1 gallons per minute compared with an average flow rate of 1.6 gallons per minute from field measurements.

Table 3.2.1-2 presents data comparing the monthly measured values of solar energy collected with the predicted performance determined from the long term regression curve and the laboratory single panel efficiency curve. The predictions were derived by the following procedure:

1. The instantaneous operating points were computed using Equation (3).

2. The instantaneous efficiency was computed using Equation (4) with the operating point computed in Step 1 above for:

    a. The long term linear regression curve for collector array efficiency

    b. The laboratory single panel collector efficiency curve

3. The efficiencies computed in Steps 2a and 2b above were multiplied by the measured solar energy available when the collectors were operational to give two predicted values of solar energy collected.

The error data in Table 3.2.1-2 were computed from the differences between the measured and predicted values of solar energy collected according to the equation:

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: SEMCO - LOXAHATCHEE LOXAHATCHEE, FLORIDA

MONTH/YEAR	COLLECTED SOLAR ENERGY (MILLION BTU)	ERROR	
		FIELD DERIVED LONG TERM	LAB PANEL
OCT 78	0.882	0.058	0.112
NOV 78	0.698	0.005	0.017
DEC 78	0.752	0.039	0.036
JAN 79	0.680	0.009	0.022
FEB 79	0.956	0.029	0.039
MAR 79	1.037	0.059	0.073
APR 79	0.346	0.056	0.079
MAY 79	0.593	0.069	0.055
JUN 79	0.878	0.083	0.062
JUL 79	0.964	0.068	0.053
AUG 79	0.844	0.026	0.058
AVERAGE	0.785	0.061	0.069

$$\text{Error} = (A-P)/P$$

where A = Measured solar energy collected

P = Predicted solar energy collected

The computed error is then an indication of how well the particular prediction curve fitted the reality of dynamic operating conditions in the field.

The values of "Collected Solar Energy" given in Table 3.2.1-2 are not necessarily identical with the values of "Collected Solar Energy" given in Table 3.2.1-1. Any variations are due to the differences in data processing between the software programs used to generate the monthly performance report data and the component level collector analysis program. These data are shown in Table 3.2.1-2 only because they form the references from which the error data given in the table are computed.

The data from Table 3.2.1-2 illustrates that for the Semco Loxahatchee site the average error computed from the difference between the measured solar energy collected and the predicted solar energy collected based on the field derived long term collector array efficiency curve was 6.1 percent. For the curve derived from the laboratory single panel data, the error was 6.9 percent. Thus the long term collector array efficiency curve gives slightly better results than the manufacturer's laboratory single panel curve.

A histogram of collector array operating points illustrates the distribution of instantaneous values as determined by Equation (3) for the entire month. The histogram was constructed by computing the instantaneous operating point value from site instrumentation measurements at the regular data system intervals throughout the month, and counting the number of values within contiguous intervals of width 0.01 from zero to unity. The operating point histogram shows the dynamic range of collector operation during the month from which the midpoint can be ascertained. The average collector array efficiency for the month was derived by projecting the midpoint value to the appropriate efficiency curve and reading the corresponding value of efficiency.

Another characteristic of the operating point histogram is the shifting of the distribution along the operating point axis. This can be explained in terms of the characteristics of the system and the climatic factors of the site, i.e., incident solar energy and ambient temperature. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (February) and a typical summer month (August) operation. The actual midpoint which represents the average operating point for February is at 0.41 and for August at 0.35. Semco Loxahatchee is a single tank domestic hot water system where the energy contribution from the auxiliary source keeps the storage temperature relatively constant. This results in the collector inlet temperature being relatively constant. Consequently, the operating point becomes dependent on outdoor ambient temperature and incident solar energy. From Equation (3) when the temperature difference becomes larger due to the lower T_a and the incident solar energy becomes smaller, as is typical in the winter, the operating point increases and collector operation shifts to the right on the operating point histogram. The opposite situation occurs in the summer. The important point to be made from this is that the average collector efficiency, which depends on the operating point, shifts from winter to summer, assuming the higher value in the summer. The behavior is further illustrated by considering the data in Table 3.2.1-1.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the 11 month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equations (1) and (2). The values of operational collector efficiency range from a maximum of 0.38 in July '79 to a minimum of 0.28 in February '79. On the average the operational collector array efficiency exceeded the collector array efficiency which included the effect of the control system by 17 percent. This represents good performance for these collectors in the application to a single tank system.

At Semco Loxahatchee, incident solar energy totaled 39.29 million Btu (Table 3.2.1-1) for the report period. Solar energy collected by the array totaled 11.27 million Btu, giving a collector array efficiency of 29 percent. Incident solar energy, during the time of collector loop operation, was 33.34 million Btu resulting in an operational collector efficiency of 34 percent. The operational collector efficiency is considered the best measure of solar system performance because it excludes such factors as control system anomalies and scheduled system down time. It, therefore, reflects the true ability of the system to collect available solar energy when it is operating in the intended collection modes.

Additional information concerning collector array analysis in general may be found in Reference [7]. The material in the reference describes the detailed collector array analysis procedures and presents the results of analyses performed on numerous collector array installations across the United States.

3.2.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si}$$

where:

ΔQ = change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value) (STECH)

Q_{so} = energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium (STEO)

Q_{si} = energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium (STEI)

Evaluation of the system storage performance under actual system operation and weather conditions can be performed using the parameters defined above. The utility of these measured data in evaluation of the overall storage design are illustrated in the following discussion.

Table 3.2.2-1 summarizes energy supplied to storage and taken from storage during the reporting period. The average storage efficiency over this period was 31 percent. This low value of storage efficiency is attributed to the extremely low hot water loads during the first six months of the reporting period, when solar energy placed in storage would have resulted in elevated tank temperatures and would have been largely dissipated as thermal losses from the tank and system piping.

The effect of the installation of the automatic hot water load device in May 1979 is reflected in significantly increased values of storage efficiency. Storage efficiency increases because, as shown in equation (5), it is defined as the ratio of the sum of stored energy change plus stored energy output to stored energy input. During the period from October 1978 through March 1979 the load and, hence, the stored energy output were extremely low, giving storage efficiencies in the range of 0% to 17%. In March 1979, the hot water load was zero causing the stored energy output to be zero and the change in stored energy to be negative. Thus, for that particular month, the storage efficiency was zero.

It should be noted that the values of "Energy From Storage" for the months of April and May were derived from the average ratio of "Stored Energy Output" to "Stored Energy Input" for June, July and August. Since actual data was not available for April and May, the months during which the automatic load device was in operation were felt to represent realistic system performance and were, therefore, used as a basis for performance estimates in April and May.

The significant drop in average storage temperature from April 1979 to the end of the reporting period is due to the increased flow of energy to the load from the storage tank. Failure to withdraw any appreciable energy from the tank in October 1978 through March 1979 time period resulted in the retention of collected solar energy in the tank and caused the internal storage temperatures to be appreciably higher.

TABLE 3.2.2-1

STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature °F
Oct 78	1.09	0.18	0.01	17	143
Nov 78	0.94	0.05	0.01	6	150
Dec 78	0.84	0.07	0.02	10	151
Jan 79	0.81	0.05	0.03	10	152
Feb 79	0.76	0.01	-0.01	0	157
Mar 79	0.91	0.00	0.02	2	158
Apr 79	(1.15)(1)	(0.63)(2)	0.01	(60)(3)	(136)(3)
May 79	(1.03)(1)	(0.63)(2)	0.01	(60)(3)	(136)(3)
Jun 79	1.11	0.66	0.00	59	132
Jul 79	1.09	0.68	0.02	63	136
Aug 79	0.95	0.56	0.00	58	141
Total	10.68	3.52	0.12	--	--
Average	0.97	0.32	0.01	31	144

Notes:

(1) Energy to storage derived from ratio; STEI/SECA for 9 month period due to insufficient measured data.
(2) Energy from storage values are average of June, July and August because of insufficient measured data for April 1979 and May 1979.
(3) Values derived from averages of June, July and August data (when DHW auto-load device was in operation).

3.2.3 Hot Water Subsystem

The performance of the hot water subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total hot water load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy.

The performance of the Semco Loxahatchee Hot Water Subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in this table is the gross energy supplied to the auxiliary system. The value of auxiliary energy supplied multiplied by the auxiliary system efficiency gives the auxiliary thermal energy actually delivered to the load. The difference between the sum of auxiliary thermal energy plus solar energy and the hot water load is equal to the thermal (standby) losses from the hot water subsystem.

The measured solar fraction in Table 3.2.3-1 is an average weighted value for the month based on the ratio of solar energy in the hot water tank to the total energy in the hot water tank when a demand for hot water exists. This value is dependent on the daily profile of hot water usage.

For the 11-month period from October 1978 through August 1979, the solar energy system supplied a total of 8.92 million Btu to the hot water subsystem. The total hot water load for this period was 3.52 million Btu, and the weighted average monthly solar fraction was 76 percent.

The monthly average hot water load during the reporting period was 0.32 million Btu which is based on an average daily consumption of 20.28 gallons, delivered at an average temperature of 147°F and supplied to the system at an average temperature of 82°F.

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Energy Supplied (million Btu)				Hot Water Parameters			Standby Losses (million Btu)	Weighted** Solar Fraction (Percent)
	Auxiliary	Auxiliary* Thermal	Solar	Total	Gallons Used	Supply Temp(°F)	Load (million Btu)		
Oct 78	0.60	0.60	0.49	1.09	297	85	0.18	0.91	45
Nov 78	0.35	0.35	0.58	0.93	42	82	0.05	0.88	71
Dec 78	0.06	0.06	0.79	0.85	103	81	0.07	0.78	89
Jan 79	0.06	0.06	0.75	0.81	71	91	0.05	0.76	94
Feb 79	0.00	0.00	0.76	0.76	17	70	0.01	0.75	100
Mar 79	0.02	0.02	0.89	0.91	0	71	0.00	0.91	0
Apr 79	(0.12)[1]	(0.12)[1]	(0.93)[1]	1.05	(1253)[1]	(82)[2]	(0.63)[1]	0.42	(88)[1]
May 79	(0.12)[1]	(0.12)[1]	(0.93)[1]	1.05	(1253)[1]	(82)[2]	(0.63)[1]	0.42	(88)[1]
Jun 79	0.17	0.17	0.95	1.12	1327	84	0.66	0.46	86
Jul 79	0.11	0.11	0.98	1.09	1359	85	0.68	0.41	89
Aug 79	0.09	0.09	0.87	0.96	1072	85	0.56	0.40	90
Total	1.70	1.70	8.92	10.62	6794	--	3.52	7.10	--
Average	0.15	0.15	0.81	0.97	618	82	0.32	0.65	76

*Auxiliary Thermal (the thermal energy applied to the load)
**Weighted Solar Fraction is computed at the time hot water is actually used.

NOTES:
1. Values are average of June, July and August, due to insufficient measured data for April and May 1979.
2. Eleven month average used because of insufficient measured data for the month.

For each month an average of 0.81 million Btu of solar energy and 0.15 million Btu of auxiliary thermal electrical energy were supplied to the hot water subsystem. Since the average monthly hot water load was 0.32 million Btu, an average of 0.65 million Btu was, therefore, lost from the hot water tank each month. This is based on the hot water tank temperature being constant on a long-term basis. That this assumption is correct, is verified by the negligible change in stored energy of 0.01 million Btu from Table 3.2.2-1.

For the October 1978 through April 1979 time period the hot water load was so low that meaningful analysis of system data was extremely difficult. This was due to the unoccupied status of the house. In May 1979, a timer controlled, servo-load device was installed to provide simulated hot water usage. The device was set for a nominal usage rate of 50 gallons per day; a rate which was essentially sustained through June, July and August 1979. The primary effect of the increased hot water load, provided by this device, was to shift the allocation of available solar energy to a nearly equal division between the satisfaction of load requirements and the replenishment of standby losses. Prior to installation of the automatic load device, the available solar energy had been almost entirely utilized to offset standby losses from the hot water tank.

The hot water load was negligible during the period of December 1978 through March 1979 (values ranged from zero to a maximum of 0.07 million Btu) and 97 to 100 percent of the standby losses were supplied by solar energy. Thus the auxiliary energy requirements varied from zero in February 1979 to 0.06 million Btu in December 1978 and January 1979. The continuing unoccupied status of the house in March 1979 and the absence of any cleaning or maintenance activities, requiring the use of hot water, resulted in zero hot water load and zero solar fraction for that month.

Emphasis, for this report period, should be given to the data for the three month period of June through August 1979 because of the more realistic hot water load conditions. These load requirements increased the demand for energy and allowed solar energy to fill a larger proportion of that demand as shown by solar fraction values averaging 88 percent for these three months. Consequently, it can be concluded that the system effectively met the design goal for this time period which predicated that 90 percent of the domestic hot water energy requirements be met by the solar energy system. A usage rate of 75 gallons, normal occupancy, per day over the entire eleven month reporting period would have benefitted the system to the extent that the design goal would have been met.

4. OPERATING ENERGY

Operating energy is defined as the energy required to transport solar energy to the point of use. Total operating energy for the Semco Loxahatchee Solar Energy System consists only of the energy required to perform Solar Energy Collection and Storage (ECSS) operations using the collector loop pump (EP100 - Figure 2-1, System Schematic). Operating energies for the system performance evaluation period are presented in Table 4-1.

Operating energy is further defined to include electrical energy that is used to support a subsystem without affecting its thermal state. Due to the single tank design and, hence, application of a single pump there is no separate hot water subsystem support requiring an expenditure of operating energy. The only operating energy in the system is the operating energy for this single pump (EP100) which is allocated against ECSS and total system operating energy.

The Semco Loxahatchee System's single tank design is typical of solar domestic hot water systems for small residential applications. In addition to the initial cost advantage of a single tank over a two tank system, the one tank design allows the replenishment of standby thermal losses with solar energy which is not possible in a two tank system. The use of a single pump for collector loop operation, with distribution to the loads by city water pressure, serves to minimize operating energy and provides for control simplicity. For the October 1978 through August 1979 period, covered by this report, a total of 0.75 million Btu of operating energy was consumed. During the report period, a total of 11.27 (3302 Kwh) million Btu of solar energy (Table 3.2.1-1) was supplied to the total system load. Therefore, for every one million Btu of solar energy delivered to the load, 0.07 million Btu (20 Kwh) of electrical operating energy was expended.

TABLE 4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Hot Water Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Oct 78	0.07	0	0.07
Nov 78	0.08	0	0.08
Dec 78	0.06	0	0.06
Jan 79	0.06	0	0.06
Feb 79	0.07	0	0.07
Mar 79	0.07	0	0.07
Apr 79	0.07	0	0.07
May 79	0.07	0	0.07
Jun 79	0.07	0	0.07
Jul 79	0.07	0	0.07
Aug 79	0.06	0	0.06
Total	0.75	0	0.75
Average	0.07	0	0.07

5. ENERGY SAVINGS

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution. The resulting energy savings are then adjusted to reflect the thermal conversion efficiency of the auxiliary source being supplanted by solar energy. For Semco Loxahatchee the auxiliary source being supplanted is an electric immersion heater with the commonly assumed 100 percent conversion efficiency of electrical to thermal energy for such devices.

Energy savings for October 1978 through August 1979 are presented in Table 5-1. For this performance evaluation time period, the average hot water subsystem monthly savings were 0.78 million Btu. After the Energy Collection and Storage Subsystem (ECSS) operating energy was deducted, the average net monthly electrical savings were 0.72 million Btu, or 209 Kwh. For the overall time period covered by this report the total net savings were 7.87 million Btu or 2304 Kwh. Based on the projected design load of an average of 1.125 million Btu per month [2] and assuming that the 90 percent solar fraction stated as a design goal [2] had been achieved, the projected savings for the report period was 11.14 million Btu or 3261 Kwh. The Semco Loxahatchee solar energy system thus attained approximately 71% of its savings potential during this reporting period.

TABLE 5-1

ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)	ECSS Operating Energy (Million Btu)	Net Savings Electrical	
	Hot Water		Million Btu	kwh
Oct 78	0.49	0.07	0.42	123
Nov 78	0.58	0.08	0.50	146
Dec 78	0.79	0.06	0.73	214
Jan 79	0.75	0.06	0.69	202
Feb 79	0.76	0.07	0.69	202
Mar 79	0.89	0.07	0.82	240
Apr 79	0.78	0.07	0.71	208
May 79	0.78	0.07	0.71	208
Jun 79	0.95	0.07	0.88	258
Jul 79	0.98	0.07	0.91	266
Aug 79	0.87	0.06	0.81	237
Total	8.62	0.75	7.87	2304
Average	0.78	0.07	0.72	209

6. MAINTENANCE

This section includes the solar energy system maintenance performed during the seasonal report period, October 1978 through August 1979. Maintenance data on the instrumentation system is not included in this report.

Only one significant maintenance action was performed at the Semco Loxahatchee site during the performance report period.

November 1978 - A check valve in the collector loop was inspected as a possible cause of thermosiphon flow at night which had resulted in the unintentional rejection of solar energy. The check valve was found missing a spring and was replaced with a new unit. This repair, which required about four hours to complete, was performed by the installing contractor for the solar system.

7. SUMMARY AND CONCLUSIONS

For the report period October 1978 through August 1979, the average measured daily incident solar energy in the plane of the collector was 1469 Btu/ft^2 which was about 1 percent below the long term value. The average daily outdoor ambient temperature was 74°F which is comparable with the long term average of 75°F. Consequently, weather conditions at the site had little adverse influence on system operation.

The incident solar energy for the 11-month period totaled 39.29 million Btu. Incident solar energy while the collector loop was operating was 33.34 million Btu and collected solar energy totaled 11.27 million Btu. This gives a collector operational efficiency of 34 percent. The 18 percent difference between the incident and operational incident solar energy is an acceptable value which indicates the control system is operating in the expected manner. Collector analysis data indicates the collector is operating at an efficiency approximately 6 percent greater than expected. This is attributed to a 45 percent greater flow than used in collector manufacturer's tests.

The hot water load was low for the first eight months of the 11-month period due to the house being unoccupied. An automatic load device was installed in May of 1979 and boosted the load to an average of 56 percent of the design load. The last three months are emphasized as representing nominal system operation. The average solar fraction of 88 percent for this three-month period indicates that the system design goal of 90 percent was reasonable for the summer months.

Electrical energy savings at the site were a net total value of 7.87 million Btu (2347 Kwh) after the 0.75 million Btu of operating energy required to operate the collector loop circulating pump were subtracted. The energy savings due to solar were less than the system's potential because of the low hot water loads. If the load had been as great as the system was designed for, a net energy savings approaching and possibly exceeding 1[illegible] million Btu are projected.

8.0 REFERENCES

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS

AND

SOLAR TERMS

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the reported collector array efficiency.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow to and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary fossil fuel, and electrical auxiliary thermal energy, and the operating energy for the subsystem. In addition, the solar energy supplied to the subsystem, along with solar fraction is tabulated. The load of the subsystem is tabulated and used to compute the estimated electrical and fossil fuel savings of the subsystem. The load of the subsystem is further identified by tabulating the supply water temperature, and the outlet hot water temperature, and the total hot water consumption.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to directly affect the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- <u>AUXILIARY ELECTRICAL FUEL</u> (HWAE) is the amount of electrical energy supplied directly to the subsystem.

- <u>ELECTRICAL ENERGY SAVINGS</u> (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- <u>SUPPLY WATER TEMPERATURE</u> (TSW) is the average inlet temperature of the water supplied to the subsystem.

- <u>AVERAGE HOT WATER TEMPERATURE</u> (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.

- <u>HOT WATER USED</u> (HWCSM) is the volume of water used.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the Development Program. It is tabulated in this report for two purposes (1) as a measure of the conditions prevalent during the operation of the system at the site, and (2) as a historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is the accumulated total solar energy incident upon the gross collector array measured at the site.
- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.
- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS
SEMCO LOXAHATCHEE

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR SEMCO LOXAHATCHEE

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. Examples of these general forms are as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the measured power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

II. PERFORMANCE EQUATIONS

The performance equations for Semco Loxahatchee used for the data evaluation of this report are contained in the following pages and have been included for technical reference and information.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

SITE SUMMARY REPORT:

INCIDENT SOLAR ENERGY (BTU)

$$= (1/60)\ \Sigma\ [I001 \times AREA] \times \Delta\tau$$

INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT)

$$= (1/60)\ \Sigma\ I001 \times \Delta\tau$$

COLLECTED SOLAR ENERGY (BTU)

$$= \Sigma\ [M100 \times CPT100M2 \times (T101 - T100)] \times \Delta\tau$$

WHERE CPT100M2 IS THE SPECIFIC HEAT VALUE OF WATER AS A FUNCTION OF TEMPERATURE

COLLECTED SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT.)

$$= \Sigma\ [M100 \times CPT100M2 \times (T101 - T100)/AREA] \times \Delta\tau$$

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

$$= (1/60)\ \Sigma\ [T001] \times \Delta\tau$$

SOLAR ENERGY TO LOAD (BTU)

= COLLECTED SOLAR ENERGY

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

COLLECTOR ARRAY EFFICIENCY = SOLAR ENERGY COLLECTED/INCIDENT SOLAR ENERGY

OPERATIONAL INCIDENT SOLAR ENERGY (BTU/SQ FT)

= $1/60\ (I001 \times AREA) \times \Delta\tau$ WHENEVER COLLECTOR PUMP IS RUNNING

ECSS OPERATING ENERGY (BTU)

$$= (3413/60)\ \Sigma\ (EP100) \times \Delta\tau$$

LOAD SUBSYSTEM SUMMARY:

HOT WATER AUXILIARY ELECTRICAL ENERGY (BTU)

$$= (3413/60)\ \Sigma(EP300) \times \Delta\tau$$

HOT WATER AUXILIARY THERMAL ENERGY = HOT WATER AUXILIARY ELECTRICAL ENERGY

ENERGY TO STORAGE (BTU)

= SOLAR ENERGY TO LOAD + HOT WATER AUXILIARY THERMAL ENERGY

ENERGY FROM STORAGE (BTU)

= HOT WATER LOAD

CHANGE IN STORED ENERGY (BTU)

= STORAGE CAPACITY x [HEAT CONTENT PREVIOUS HOUR - HEAT CONTENT PRESENT HOUR]

WHERE STORAGE CAPACITY IS THE ACTIVE VOLUME OF THE TANK

STORAGE AVERAGE TEMP (DEGREE F)

= $(1/60)\ \Sigma\ [(T201 + T202 + T203) / 3] \times \Delta\tau$

STORAGE EFFICIENCY

= (CHANGE IN STORED ENERGY + ENERGY FROM STORAGE)/ENERGY TO STORAGE

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

DAYTIME AMBIENT TEMP (DEGREES F)

= $(1/360)\ \Sigma\ [T001] \times \Delta\tau$

(COMPUTED ONLY ± 3 HOURS FROM SOLAR NOON)

OPERATING ENERGY (BTU):

TOTAL OPERATING ENERGY (BTU)

= ECSS OPERATING ENERGY

TOTAL AUXILIARY THERMAL ENERGY

= HOT WATER AUXILIARY THERMAL ENERGY

TOTAL AUXILIARY ELECTRIC FUEL (BTU)

= HOT WATER AUXILIARY ELECTRICAL ENERGY

TEMPERATURE OF COLD WATER SUPPLY (°F)

= TSW2/TWS1 (PERFORMED AT THE END OF EACH HOUR)

WHERE $TSW2 = \Sigma\ M301 \times T300 \times \Delta\tau$

$TSW1 = \Sigma\ M301 \times \Delta\tau$

TEMPERATURE OF HOT WATER SUPPLY (°F) = THW1/TSW1 (PERFORMED AT END OF EACH HOUR)

WHERE $THW1 = \Sigma\ M301 \times T301 \times \Delta\tau$

HOT WATER ELECTRICAL SAVINGS = SOLAR ENERGY TO LOAD

HOT WATER LOAD = Σ [M301 x CP1 x (T301 - T300) x $\Delta\tau$

CP1 = SPECIFIC HEAT OF WATER AS A FUNCTION OF TEMPERATURE

HOT WATER SOLAR FRACTION (PERCENT)

= 100 x (HOT WATER SOLAR ENERGY SUPPLIED TO CONSUMPTION LOAD/ HOT WATER LOAD)

HOT WATER CONSUMPTION (GAL) = Σ WD301 x $\Delta\tau$

WHERE WD301 IS HOT WATER CONSUMPTION RATE DERIVED FROM W301

TOTAL ELECTRICAL SAVINGS

= HOT WATER ELECTRICAL SAVINGS - ECSS OPERATING ENERGY

TOTAL ENERGY CONSUMED (BTU)

= AUXILIARY THERMAL ENERGY + OPERATING ENERGY + SOLAR ENERGY COLLECTED

SYSTEM LOAD (BTU) = HOT WATER LOAD

SOLAR ENERGY USED:

HOT WATER SOLAR ENERGY USED (BTU) = SOLAR ENERGY TO LOAD

TOTAL SOLAR ENERGY TO LOADS (BTU)

= HOT WATER SOLAR ENERGY USED

SYSTEM PERFORMANCE FACTOR

= SYSTEM LOAD/3.33 x (AUXILIARY ELECTRIC FUEL + SYSTEM OPERATING ENERGY)

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

The environmental estimates given in this appendix provide a point of reference for evaluation of weather conditions as reported in the Monthly Performance Reports and Solar Energy System Performance Evaluations issued by the Solar Heating, Cooling and Hot Water Development Program. As such, the information presented can be useful in prediction of long-term system performance.

Environmental estimates for this site include the following monthly averages: extraterrestrial insolation, insolation on a horizontal plane at the site, insolation in the tilt plane of the collection surface, ambient temperature, heating degree-days, and cooling degree-days. Estimation procedures and data sources are detailed in the following paragraphs.

The preferred source of long-term temperature and insolation data is "Input Data for Solar Systems" (IDSS) [1] since this has been recognized as the solar standard. The IDSS data are used whenever possible in these environmental estimates for both insolation and temperature related sources; however, a secondary source used for insolation data is the Climatic Atlas of the United States [2], and for temperature related data, the secondary source is "Local Climatological Data" [3].

Since the available long-term insolation data are only given for a horizontal surface, solar collection subsystem orientation information is used in an algorithm [4] to calculate the insolation expected in the tilt plane of the collector. This calculation is made using a ground reflectance of 0.2.

SITE: SEMCO FT. LAUD. 27.

LOCATION: FT LAUDERDAL.FL

ANALYST: R. MANDT

EDRIVE NO.: 72.

COLLECTOR TILT: 36.70 (DEGREES)

COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 26.70 (DEGREES)

RUN DATE: 08/09/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	2022.	1036.	0.51229	1.401	1451.	64	113	67.
FEB	2408.	1283.	0.53276	1.252	1606.	76	137	67.
MAR	2855.	1595.	0.55530	1.090	1729.	20	198	71.
APR	3253.	1844.	0.56678	0.939	1731.	0	289	75.
MAY	3478.	1844.	0.52997	0.841	1551.	0	398	78.
JUN	3550.	1707.	0.48083	0.808	1380.	0	475	81.
JUL	3504.	1770.	0.50509	0.822	1454.	0	532	82.
AUG	3328.	1641.	0.49303	0.896	1470.	0	548	83.
SEP	2990.	1442.	0.48213	1.017	1466.	0	499	82.
OCT	2533.	1272.	0.50226	1.184	1506.	0	390	78.
NOV	2109.	1099.	0.52097	1.362	1497.	16	219	72.
DEC	1908.	995.	0.52170	1.457	1451.	64	152	69.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

REFERENCES

[1] Cinquemani, V., et al. "Input Data for Solar Systems." Prepared for the U.S. Department of Energy by the National Climatic Center, Asheville, NC, 1978.

[2] United States Department of Commerce, Climatic Atlas of the United States, Environmental Data Service, Reprinted by the National Oceanic and Atmospheric Administration, Washington, DC, 1977.

[3] United States Department of Commerce, "Local Climatological Data," Environmental Data Service, National Oceanic and Atmospheric Administration, Asheville, NC, 1977.

[4] Klein, S. A., "Calculation of Monthly Average Insolation on Tilted Surfaces," Joint Conference 1976 of the International Solar Energy Society and the Solar Energy Society of Canada, Inc., Winnipeg, August 15-20, 1976.

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