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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR SEMCO, MACON, GEORGIA

Prepared by

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George C. Marshall Space Flight Center, Alabama 35812

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 residence. The SEMCO System 80 consists of liquid (silicone) flat plate collectors, single tank, pump, controls and transport lines.

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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-Macon solar energy system is located in one side of a duplex in a public housing project in Macon, Georgia. The system is designed to provide domestic hot water (DHW) to the one-story residence. The hot water system has a roll-bond heat exchanger wrapped around the hot water storage tank. Silicon oil is circulated through the heat exchanger and the 80 square foot flat-plate collector array.

The collector array is composed of two panels connected in parallel and is mounted facing south at an angle of 42.7 degrees from the horizontal. The collector panels, Model 40-70-DG, are manufactured by the Solar Engineering and Manufacturing Company (SEMCO) of Deerfield Beach, Florida.

The 120-gallon hot water storage tank is glass lined steel and is externally insulated with two-inch thick, high density fiberglass. Auxiliary energy, as required to maintain a selectable minimum temperature, is provided to the hot water storage tank by a 4,500-watt electric resistance heat element. The system is shown schematically by Figure 2-1. The sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 (Reference [3]). The measurement symbol prefixes: W, T, EP, and I represent respectively: flow rate, temperature, electric power, and insolation. Figure 2-2 is a pictorial view of the Semco Macon installation.

Based on data provided by Semco in the Semco Macon system performance design specification, the DHW system is to be capable of delivering up to 75 gallons of potable hot water per day at a temperature of 140°F. System design prediction for average hot water heating load is 1,313,000 Btu/month, assuming an average cold water supply temperature of 70°F. Auxiliary hot water heating requirements will be 20 percent of the monthly load according to hot water design prediction. The only actively controlled solar operation mode is described as follows:

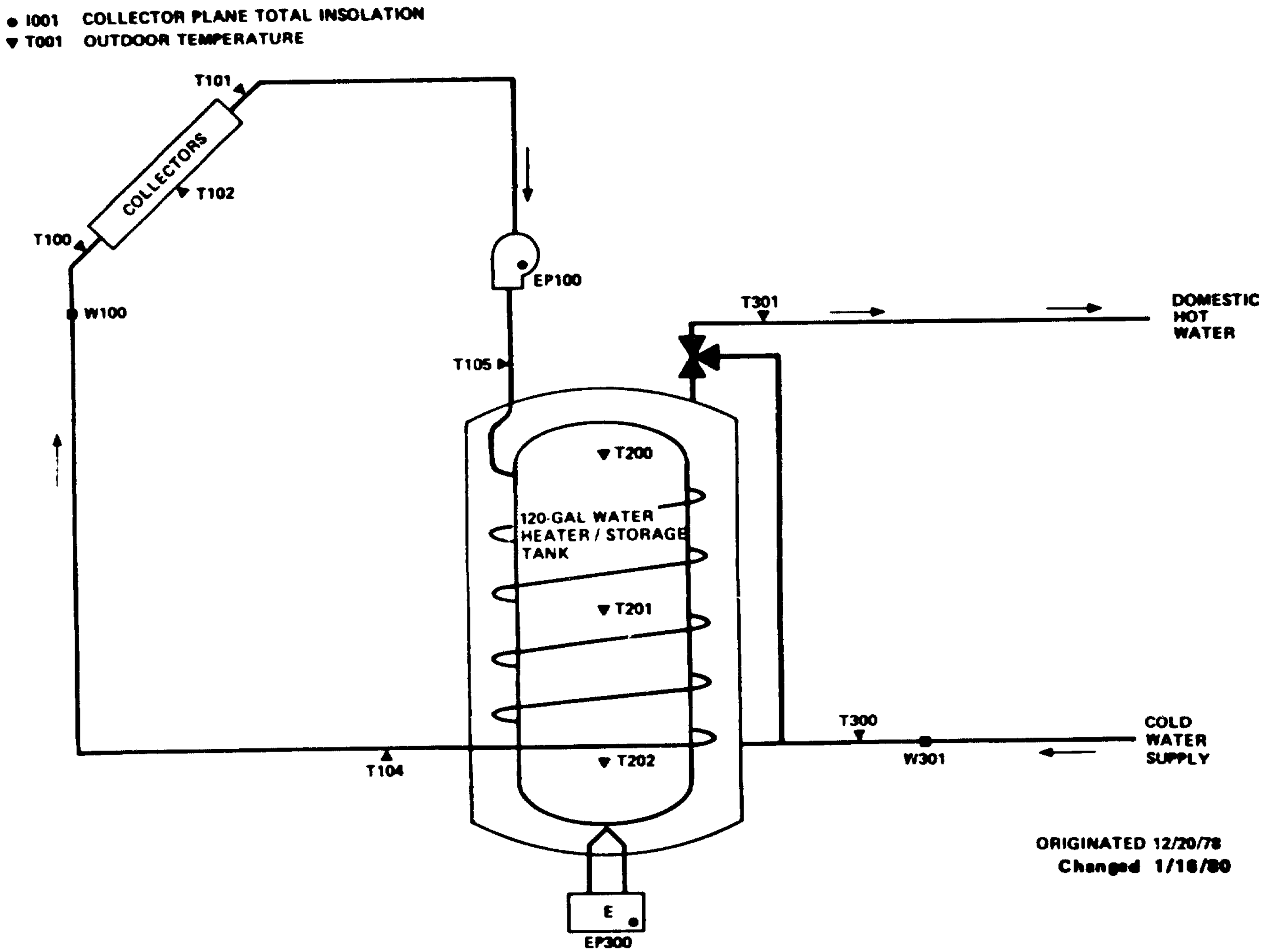

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Figure 2-1. SEMCO-MACON, Georgia, Solar Energy System Schematic

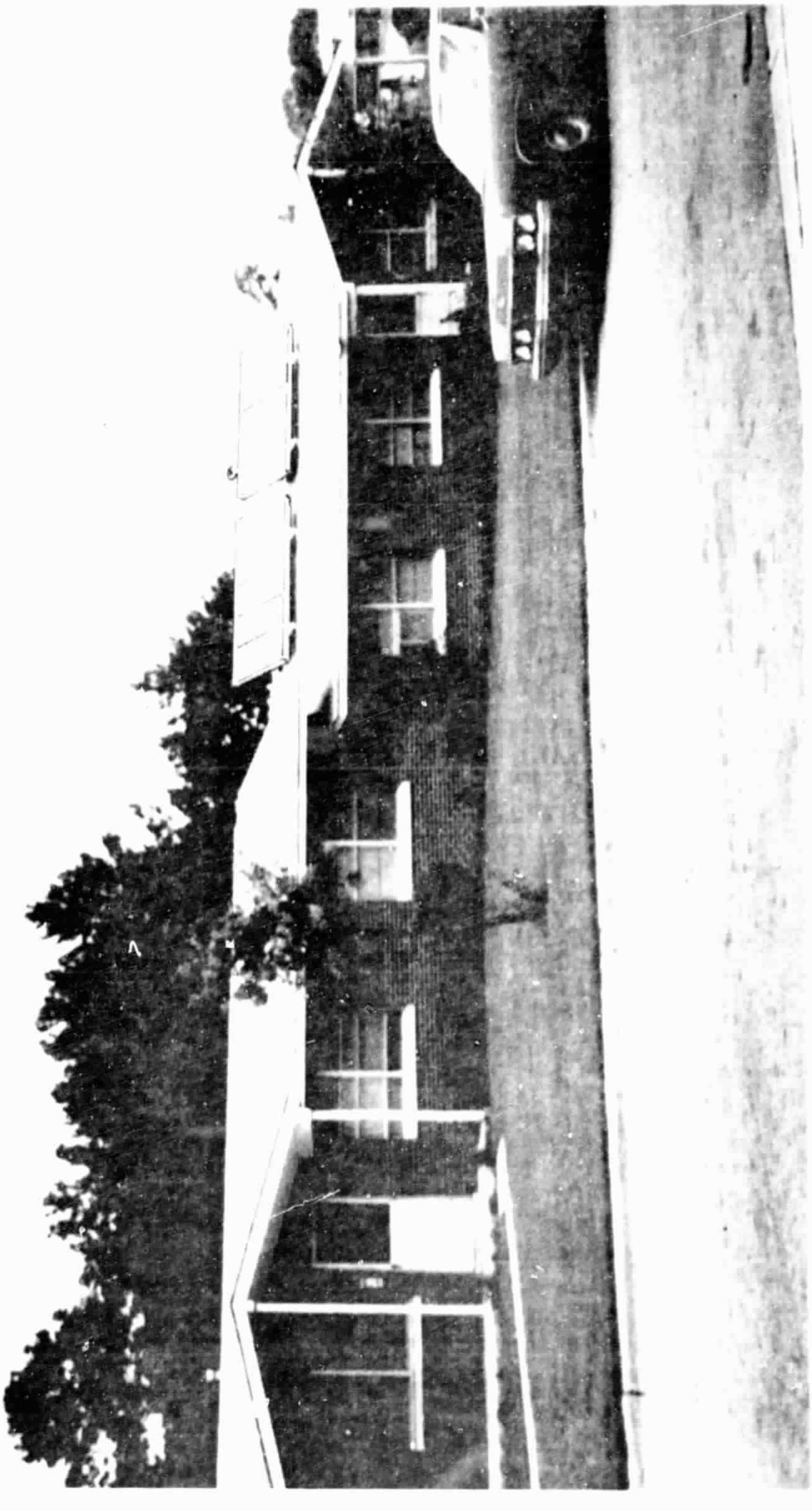


Figure 2-2. Semco Macon Pictorial

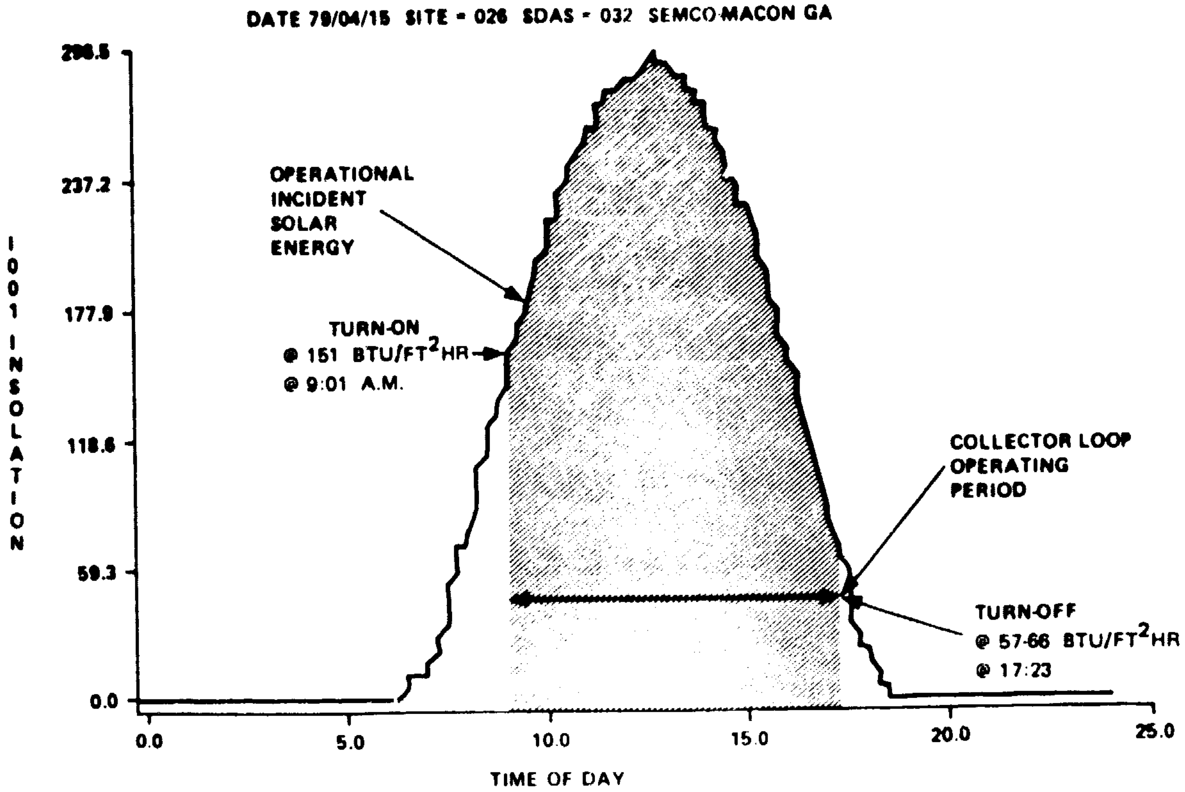
<u>Mode 1 - Collector-to-Storage</u>: This mode is entered when a differential controller recognizes that the collector absorber plate temperature exceeds the temperature in the bottom of the hot water storage tank by a fixed value (nominally 20°F). The mode is terminated when the measured differential temperature drops below a fixed value (nominally 5°F).

2.1 Typical System Operation

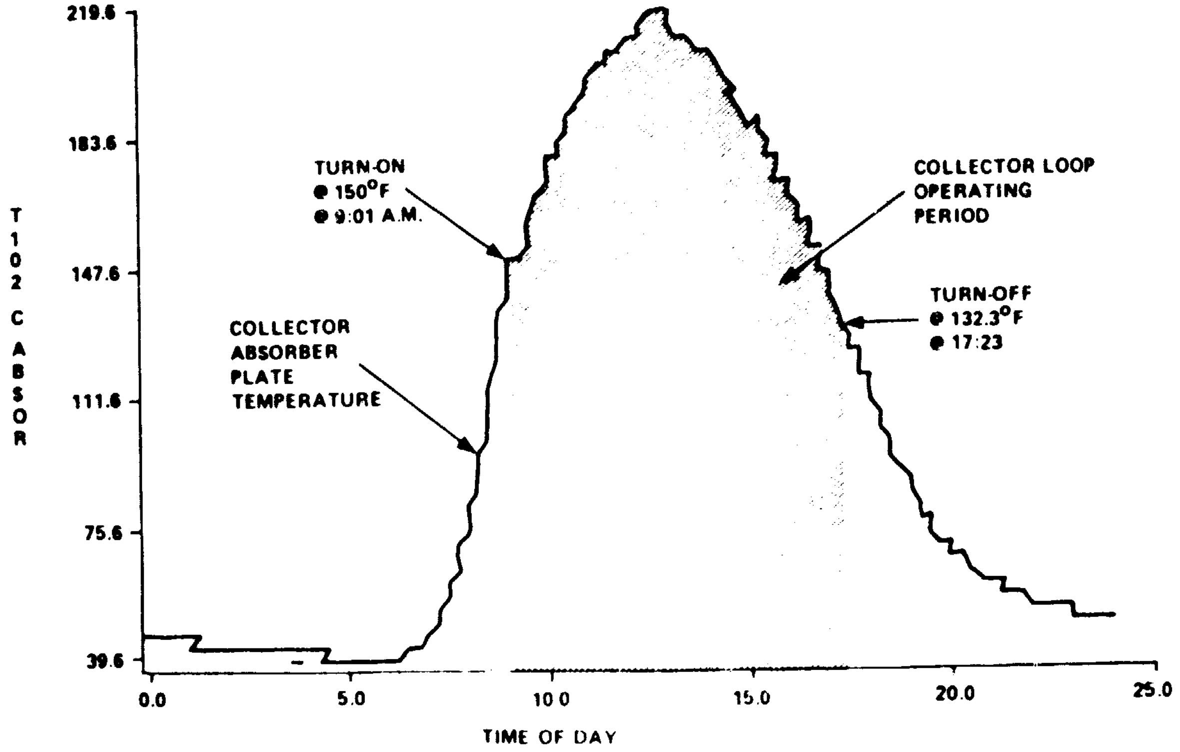
Solar energy collection and storage subsystem (ECSS) operations at the Semco Macon solar site are controlled on the basis of the sensed difference in temperatures of the collector absorber plate and the bottom of storage. Using a Hawthorne Industries Variflo Proportional Controller and a Grundfos 1/12 HP variable head circulation pump, the controller controls the pump speed to produce a flow that is proportional to the collector-to-storage temperature differential over the nominal range of 5°F to 20°F. When the collector absorber plate temperature no longer exceeds the bottom of storage temperature by at least 5°F, the collector loop flow ceases. When the collector absorber plate temperature exceeds the bottom of storage temperature, by at least 20°F, then maximum collector loop flow rates (1.4-1.5 GPM) are achieved.

A day that is believed to be typical of normal ECSS operation is illustrated by Figures 2.1-1(a) and 2.1-1(b). Figure 2.1-1(a) is a plot of insolation measurement I001 for the selected typical day. On this day collector loop pump turn-on occurred at 9:01 AM when insolation had reached a value of 151 Btu/Ft^2-Hr. Collector pump operation was continuous throughout the day until 5:23 PM when insolation had declined to 57-66 Btu/Ft^2-Hr.

Included on Figure 2.1-1(a) is a plot also of the collector absorber plate temperature measurement T102. Corresponding to the operational period shown on the plot of insolation, collector loop pump turn-on occurred when T102 was between 142 and 150°F. At this time the temperature in the bottom of storage near the control sensor was 121-122°F. Collector pump operation was continuous throughout the day until 5:23 PM when T102 had declined to 132°F. At the time of collector loop pump turn-off the temperature in the bottom of storage near the control sensor was approximately 126-127°F.



SOLAR INSOLATION VS TIME OF DAY

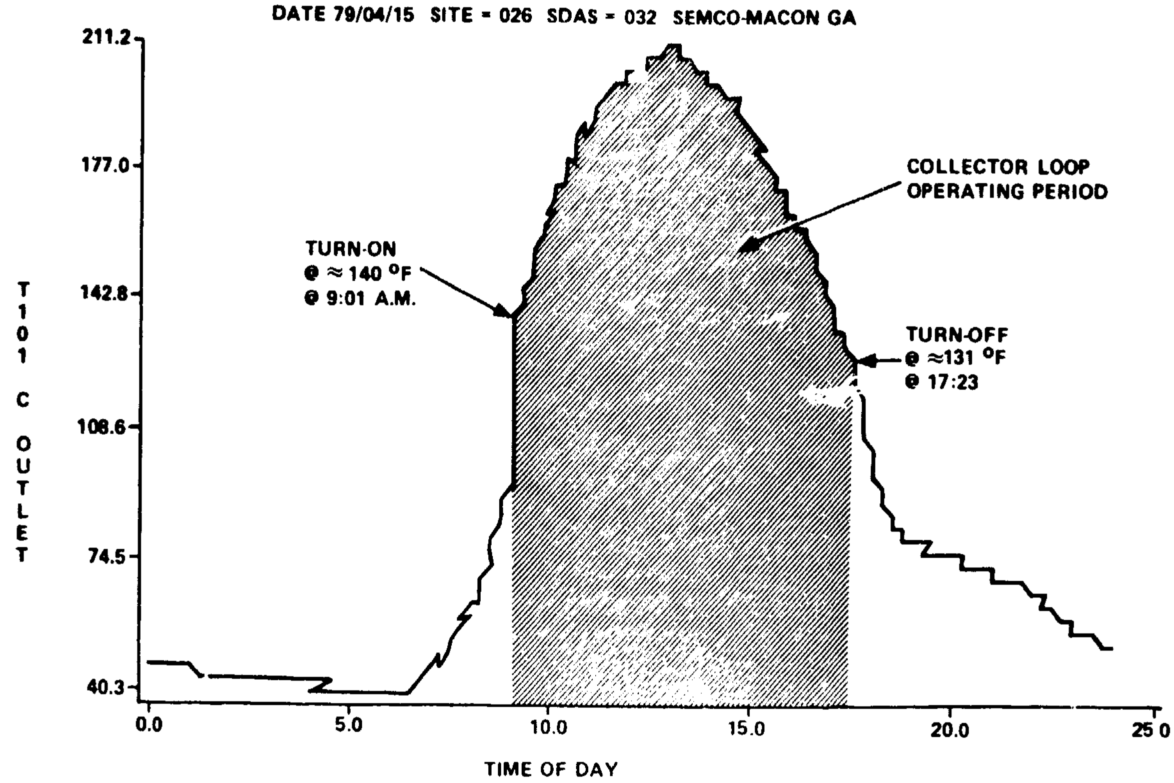


ABSORBER PLATE TEMPERATURE VS TIME OF DAY

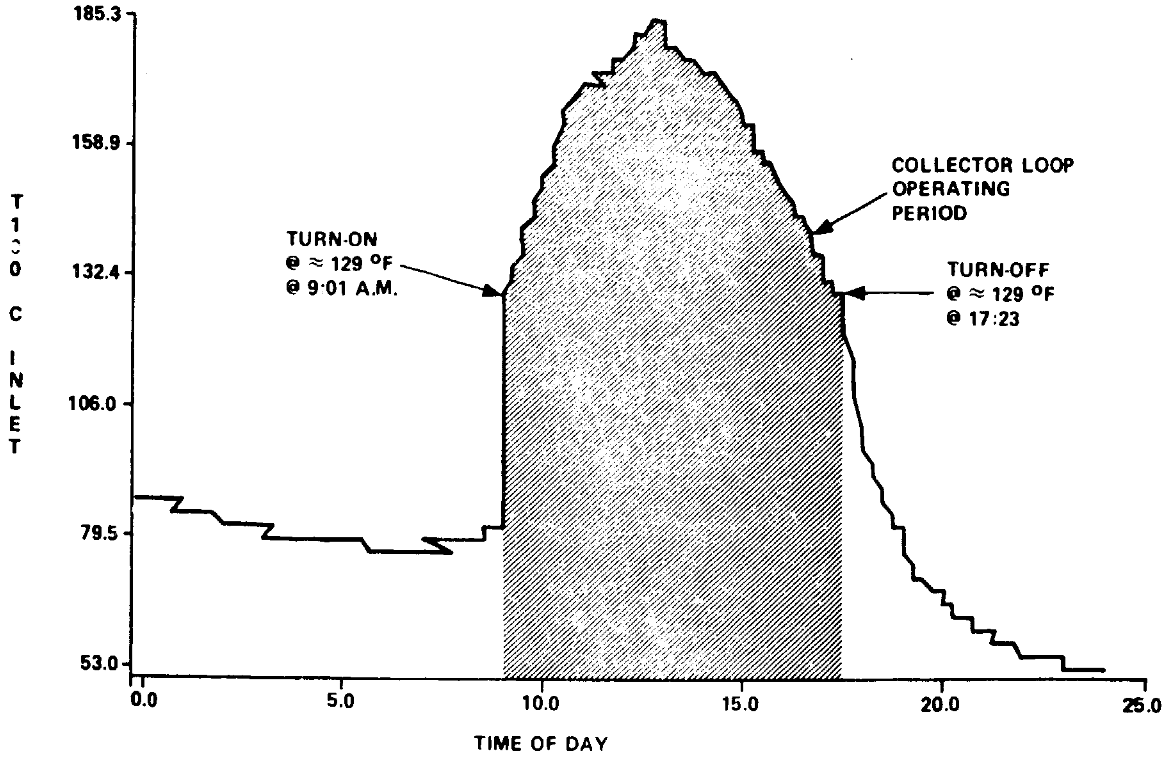
Figure 2.1-1 (a). Typical System Operating Parameters

Figure 2.1-1 (b) is a plot of collector inlet temperature, T100, and collector outlet temperature, T101, 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 129°F and collector outlet temperature was 140°F. At the time of collector loop turn-off, collector inlet temperature had returned to approximately 129°F and collector outlet temperature to 131°F.

On this particular day, chosen as typical of system operation, the system was controlled and ECSS operation performed in a manner that was predictably in accord with control system design and controller operating set points.



COLLECTOR OUTLET TEMPERATURE VS TIME OF DAY



COLLECTOR INLET TEMPERATURE VS TIME OF DAY

Figure 2.1-1 (b). Typical System Operating Parameters

2.2 System Operating Sequence

For the day selected, and discussed in Section 2.1, as representative of normal system ECSS operation, operating sequence of the Semco-Macon solar energy 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 feature 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 50 gallons. Additionally, solar energy replenished thermal energy losses of the storage tank during this period, such that no DHW auxiliary heating was required until the 15 gallon DHW usage which occurred at approximately 10:00 PM. On this day the hot water solar fraction of the load was tabulated to be 77 percent.

A different operating sequence was observed on numerous occasions during the mid-winter months at the Semco site. Due to a change, either in occupancy or daily schedules, hot water usage was predominantely in late evening or early morning. Under these circumstances hot water usage was out of phase with solar energy collection and storage operations and the maximum availability of solar energy. Consequently, a lower solar fraction for the hot water used might be expected even with all other factors remaining equivalent to the typical day under discussion.

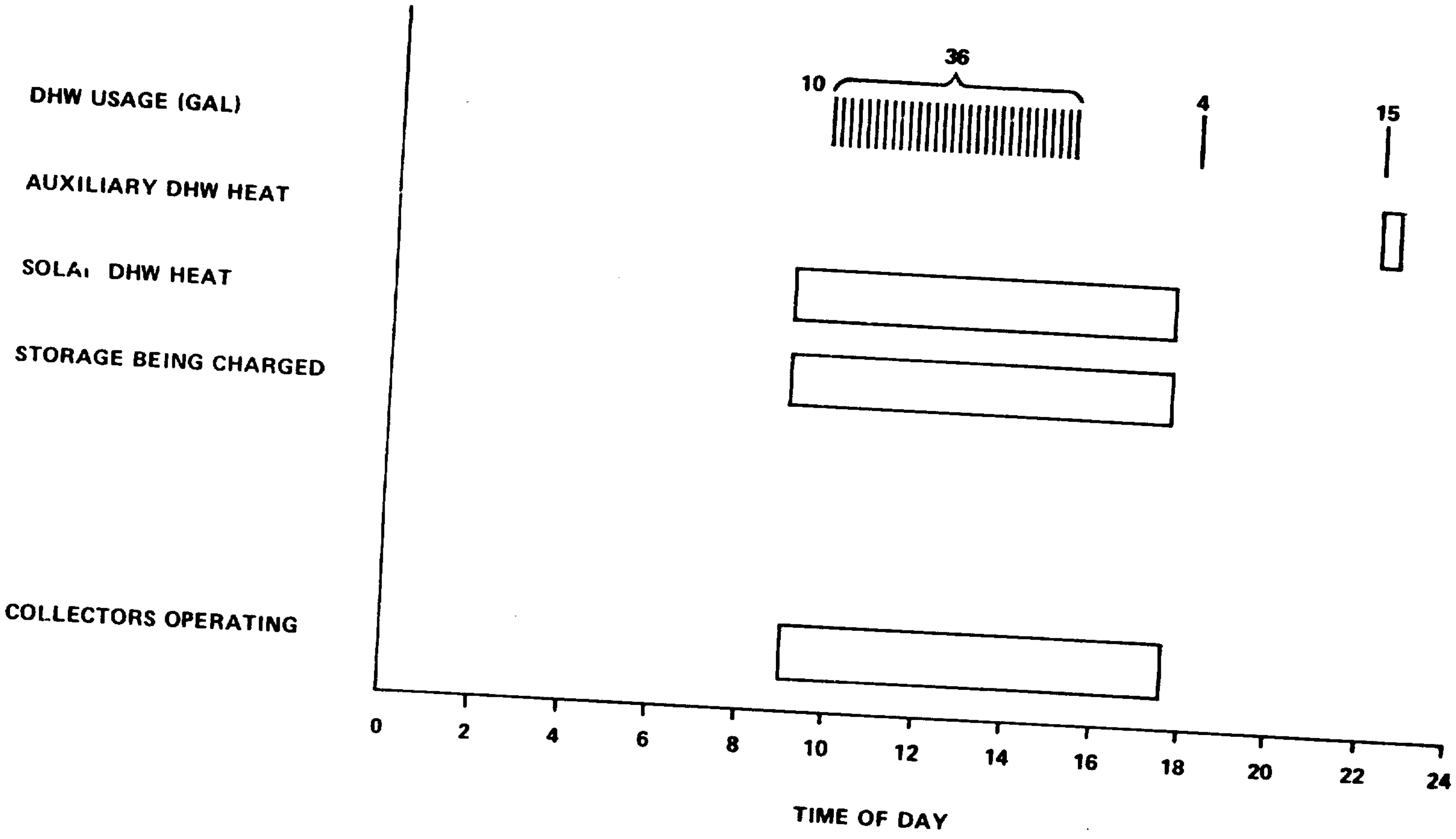


Figure 2.2-1. Typical System Operating Sequence

3. PERFORMANCE ASSESSMENT

The performance of the Semco Macon Solar Energy System has been evaluated for the May 1978 through April 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 Macon Solar Energy System located in Macon, Georgia. 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 May 1978 through April 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:

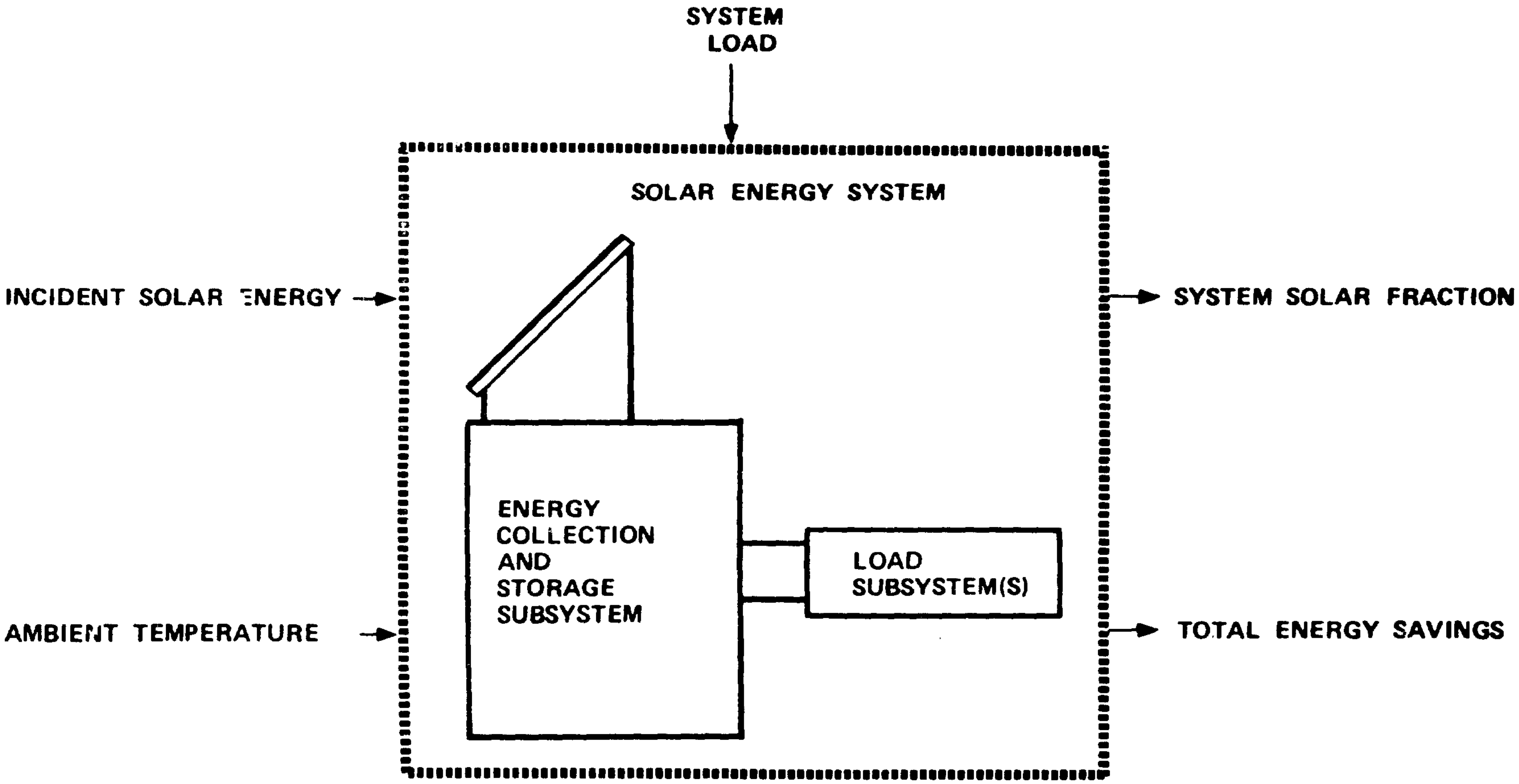


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

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 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 Macon site for the twelve month report period, the long term average daily incident solar energy in the plane of the collector was 1456 Btu/ft^2. The average daily measured value was 1343 Btu/ft^2 which is about 8 percent below the long term value. On a monthly basis, June of 1978 was the worst month with an average daily measured value of incident solar energy 23 percent below the long term average daily value. November 1978 was the best month with an average daily measured value 13 percent above the long term average daily 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 65°F for the Semco Macon site which is equal to the measured value of 65°F. On a monthly basis January and February of 1979 were the worst months, temperaturewise, when the measured temperature was 4 to 6°F below the long term daily average. This two 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 led to a decrease in the total net savings.

TABLE 3.1-1
SYSTEM PERFORMANCE SUMMARY
SEMCO MACON

Month	Daily Incident Solar Energy per Unit Area @42.7° Tilt (Btu/ft^2·Day)		Ambient Temperature °F		System Load-Measured	Solar Fraction (Percent)		Total Net Energy Savings
	Measured	Long Term Average	Measured	Long Term Average	(Million Btu)	Measured	Expected	(Million Btu)
May 78(3)	1305	1572	70	74	1.17	(4)	52	0.74
Jun 78(3)	1173	1514	77	80	0.81	(4)	52	0.65
Jul 78(1,3)	1184	1448	80	81	0.85(2)	(4)	62	C.89
Aug 78	1443	1542	82	81	0.88	71	63	0.89
Sep 78	1363	1510	78	76	0.88	67	60	0.78
Oct 78	1759	1599	65	66	1.08	68	70	1.07
Nov 78(1)	1601	1419	59	55	1.17	(4)	54	0.74
Dec 78	1157	1159	51	48	1.59	30	36	0.48
Jan 79	1103	1164	42	48	1.33	30	36	0.56
Feb 79	1118	1352	46	50	1.29	31	37	0.53
Mar 79	1535	1540	59	57	1.78	44	52	0.93
Apr 79	1374	1651	66	66	1.08	55	59	0.72
Total	16115	17470	--	--	13.89	--	--	8.98
Average	1343	1456	65	65	1.16	50	53	0.75

NOTES:

(1) Data based on 9 days of data for July 1978; 7 days of data for November 1978.
(2) July 1978 system load based on average load for summer months (June, August and September)
(3) May 1978 solar energy collection and usage based on incident solar energy and assumed collector efficiency of 26%; June - 27%, July - 28% and November - 25%.
(4) No valid data available due to data system/transmission problems.

The effect of system load and ambient temperature on the performance of the Semco Macon Solar Energy System can be seen by reference to Table 3.1-1. The maximum solar fraction of 71 percent was achieved in July and August when system load was lowest and ambient temperature the highest. Conversely, the minimum solar fraction of 30 percent was attained during December and January when the highest load and minimum outdoor temperature of the reporting period occurred. This performance was predictable because the increased temperature difference between collector fluid and ambient air results in increased collector losses and, hence, a reduction in the amount of solar energy collected.

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 the 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 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 net energy savings for the Semco Macon Solar Energy System was 8.98 million Btu or 2630 kwh.

3.2 Subsystem Performance

The Semco Macon 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 Macon 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 parallel 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:

$$\eta_c = Q_s/Q_i \tag{1}$$

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.

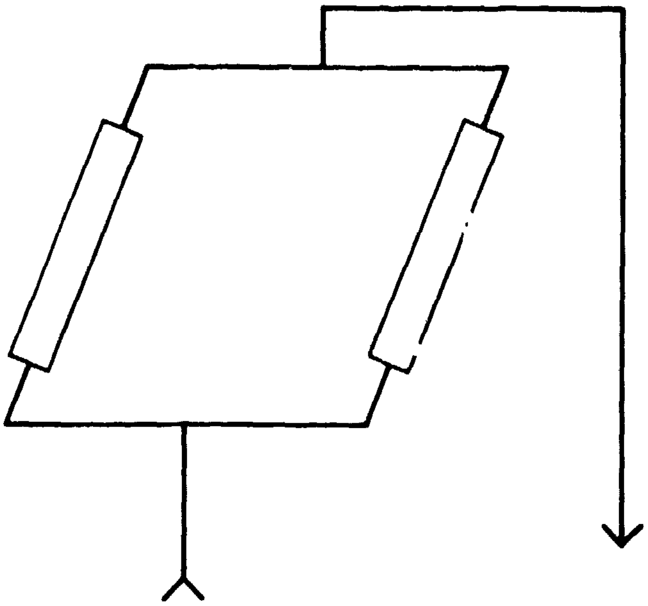


Figure 3.2.1-1 (a). Collector Array Arrangement (2 single panels)

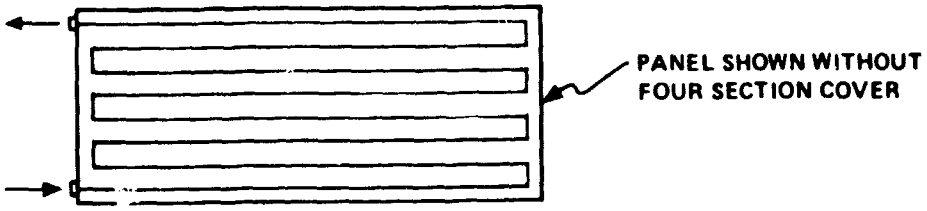


Figure 3.2.1-1 (b). Collector Panel Liquid Flow Path (serpentine)

COLLECTOR DATA

Manufacturer – SEMCO
Model – FP40-7-DG
Type – Liquid
Number of Collectors – 2
Flow Paths – 1

SITE DATA

Location – Public Housing Project
1777 Wren Avenue
Macon, Georgia
Latitude – 32.7°N
Longitude – 83.65°W
Collector Tilt – 42.7°
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 Efficiency
May 78	3.24	0.84	0.26	2.59	0.32
Jun 78	2.82	0.76	0.27	2.20	0.34
Jul 78	3.57	1.00	0.28	3.03	0.33
Aug 78	3.58	1.01	0.28	3.02	0.33
Sep 78	3.27	0.89	0.27	2.73	0.33
Oct 78	4.36	1.19	0.27	3.81	0.31
Nov 78	3.40	0.85	0.25	2.93	0.29
Dec 78	2.87	0.63	0.22	2.34	0.27
Jan 79	2.74	0.65	0.24	2.15	0.30
Feb 79	2.50	0.59	0.24	1.96	0.30
Mar 79	3.81	1.06	0.28	3.47	0.30
Apr 79	3.30	0.85	0.26	2.98	0.29
Total	39.46	10.32	--	33.21	--
Average	3.29	0.86	0.26	2.77	0.31

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:

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

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 a significant difference between laboratory calibrated single panel collector data and the collector data determined from long term field measurements. There are two primary reasons for this difference:

- 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:

$$x_j = \frac{T_i - T_a}{I} \quad (3)$$

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:

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*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.

$$\eta_j = b - mx_j \qquad (4)$$

where η_j = Collector efficiency corresponding to the jth instant

b = Intercept on the efficiency axis

$(-)m$ = Slope

x_j = Collector operating point at jth 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 Hottell-Whillier-Bliss equation:

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

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:

$$b = F_R\tau\alpha \quad \text{and} \quad m = F_RU_L \tag{6}$$

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 heat transfer fluid at the Semco Macon site is Dow-Corning Q2-1132 silicone oil. The fluid viscosity ranges from 20 centistokes (21.52×10^{-5} ft^2/sec) at 77°F to 7 centistokes (7.532×10^{-5} ft^2/sec) at 210°F.

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*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.

This factor causes high dynamic pressure drop around the collector loop and low flow velocity. Consequently, for the pump size and piping configuration at Semco Macon, the Reynolds number is approximately 215, flow is laminar at 0.7 gallons per minute and the tube-to-fluid heat transfer coefficient is approximately 5 Btu/hr-ft^2-°F. It is, therefore, expected that the Semco Macon collector array will perform much less effectively than the laboratory single panel test (with water, at optimum flow).

Mathematically de-rating the collector performance to the measured flow rate gives the following predicted characteristic curve:

$$\eta = 0.325 - 0.536\ (T_i - T_a)/I \qquad (7)$$

The observed performance of the collector array over the period August 1978 through May 1979, with contributing measurements selected in accordance with the philosophy outlined in ASHRAE Standard 93-77, results in the following estimate of collector array performance:

$$\eta = 0.426 - 0.413\ (T_i - T_a) \qquad (8)$$

Equation (8) was derived by MSFC and documented in Report C-8, EL51 (5-80), to B. Wiesenmaier by R. D. Collins, Jr. Independent long-term collector array analysis conducted by IBM resulted in the following equation which tends to confirm the MSFC curve:

$$\eta = 0.441 - 0.36\ (T_i - T_a)/I \qquad (9)$$

However the coefficient of determination (r^2) for the IBM curve is below statistically meaningful minimums, indicating a high degree of scatter in the data points used to derive the curve. Thus, this analysis will use the MSFC-derived curve (Eq 8).

As a check against the two estimates, filtered data points have been plotted for April 16, 1979, and a linear regression line placed through the resulting scatter diagram. The resulting equation is:

$$\eta = 0.381 - 0.239\ (T_i - T_a)/I \qquad (10)$$

The three curves (Eq 7, Eq 8, and Eq 10) are plotted in Figure 3.2.1-2.

Somewhat uncharacteristically, the observed performance is considerably better than the derated prediction curve. The heat loss coefficient for the long-term case is 0.693 Btu/ft^2-hr-°F, whereas, the derated prediction heat loss coefficient is 1.18 Btu/ft^2-hr-°F, and the heat loss coefficient from the optimal laboratory test is 1.02 Btu/ft^2-hr-°F. There are no obvious causes for this great a deviation. The collectors do not gain an advantage from installation. That is, no additional insulation is obtained from the mounting bracket assembly; thus, the U_L term should be consistent with test and prediction. If, however, the collectors installed at Semco Macon represent a significant design improvement over the collectors tested by the Florida Solar Energy center and documented in FSEC #78014, the observed deviation might be explained. The data presented in Table 3.2.1-2 compares the values of the significant parameters from the observed and predicted characteristic curves.

TABLE 3.2.1-2

	F_R	F'	U_L	$\tau\alpha$	$F_R\tau\alpha$	F_RU_L
PREDICTED	0.454	0.496	1.180	0.715	0.325	-0.536
OBSERVED	0.596	0.639	0.693	0.715	0.426	-0.413

Figure 3.2.1-3 presents operating point histograms for the months of June and December. Clearly, the dominant operating point shifted to the right between June and December. This indicates that the collector array inlet

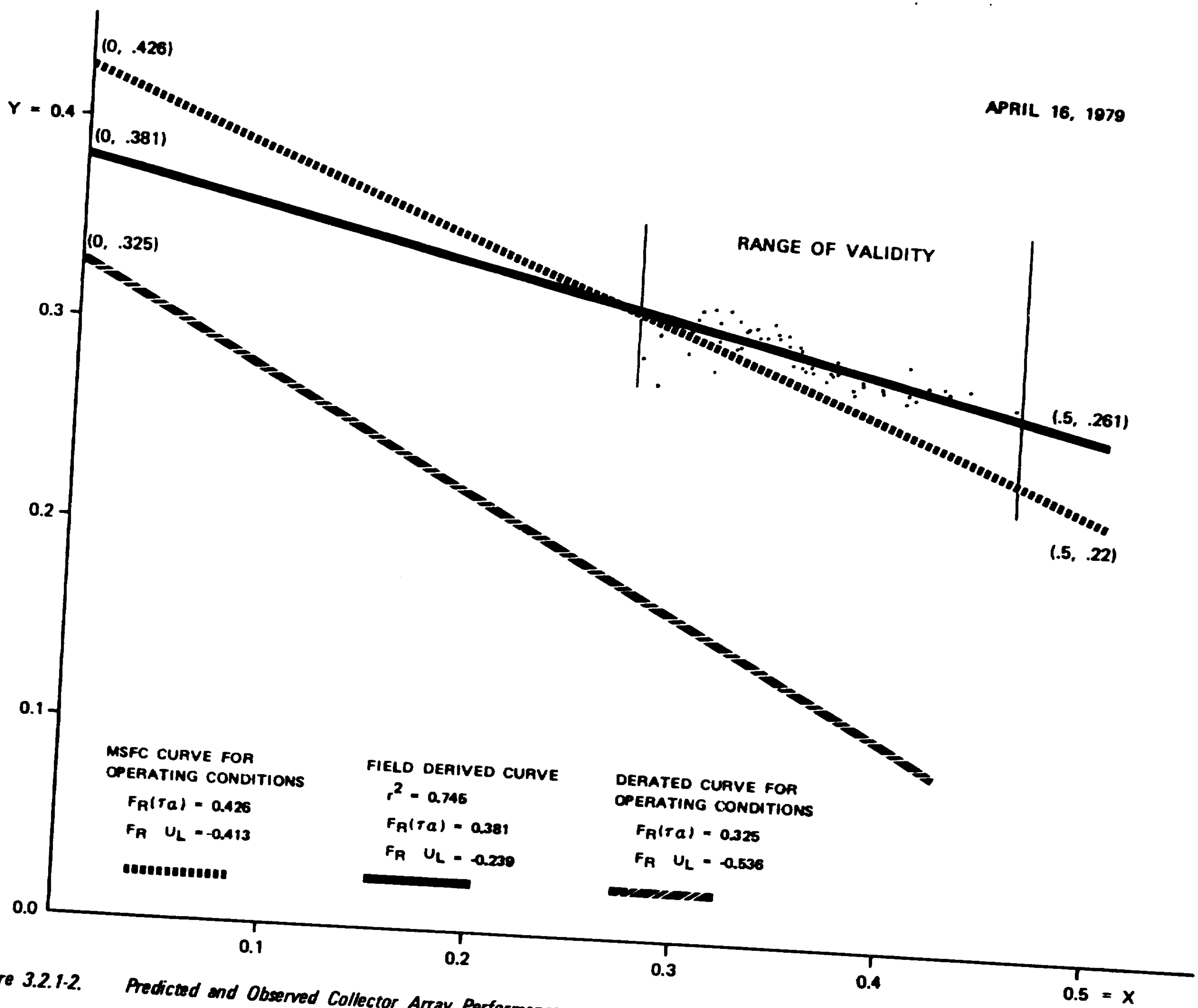

Figure 3.2.1-2. *Predicted and Observed Collector Array Performance*

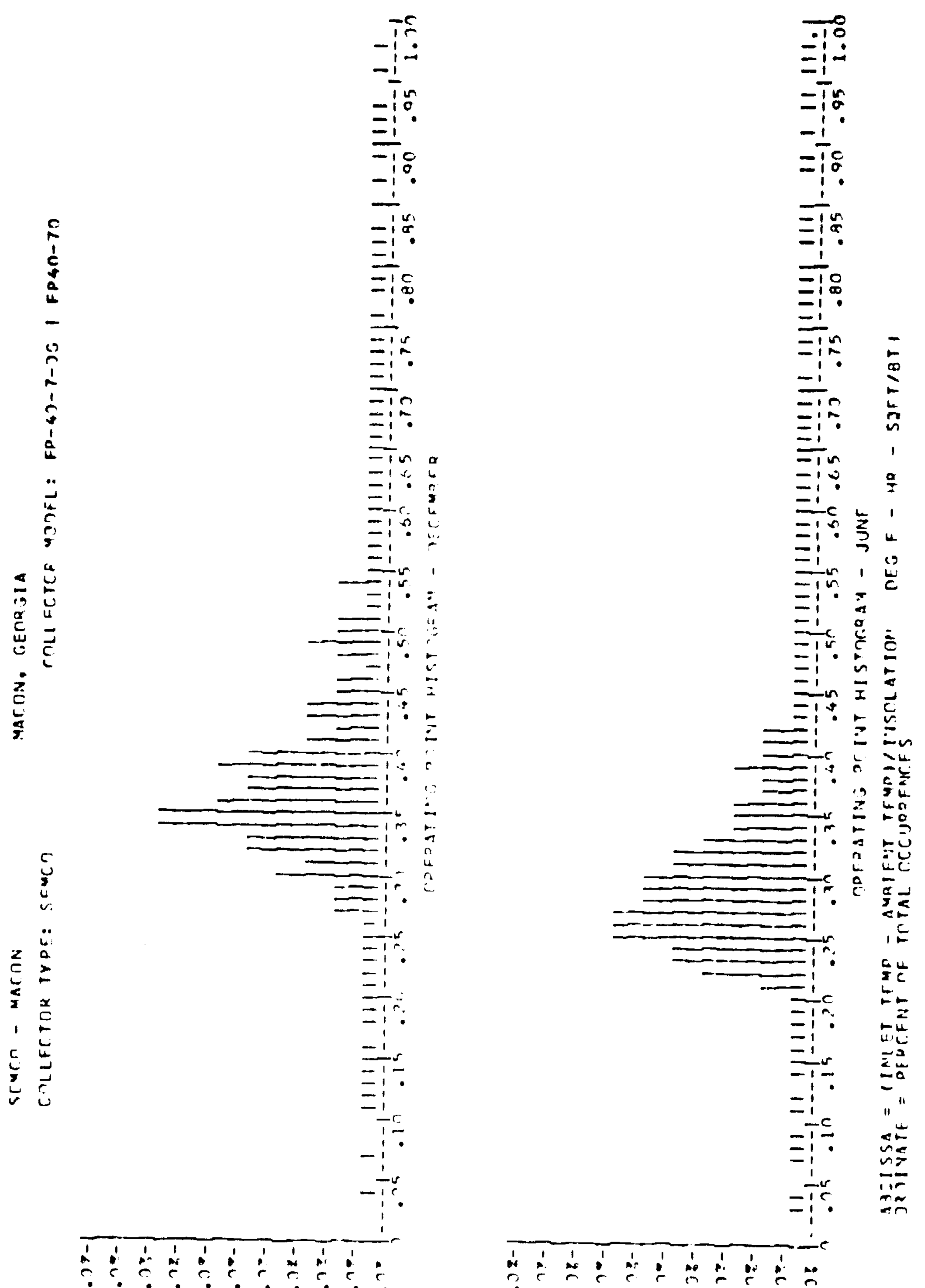

Figure 3.2.1-3. Macon Operating Point for Typical Winter and Summer Months

temperature remained relatively constant as the external ambient temperature dropped; and that the change in average insolation rate was proportionally less than the change in temperature difference. This is a characteristic of single-tank hot water systems.

Table 3.2.1-3 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 calibrated 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 3.2.1-3 were computed from the differences between the measured and predicted values of solar energy collected according to the equation:

TABLE 3.2.1-3

ENERGY GAIN COMPARISON (ANNUAL)

SITE: SEMCO MACON MACON, GEORGIA

MONTH/YEAR	COLLECTED SOLAR ENERGY (MILLION BTU)	ERROR	
		FIELD DERIVED LONG TERM	LAB PANEL
JUN 78	0.769	0.042	2.555
JUL 78	0.333	-0.054	2.171
AUG 78	0.898	-0.003	1.879
SEP 78	0.858	-0.025	1.856
OCT 78	*	*	*
NOV 78	0.260	0.035	1.988
DEC 78	0.499	0.070	2.082
JAN 79	0.634	0.058	2.239
FEB 79	0.558	0.000	1.875
MAR 79	1.043	0.006	1.782
APR 79	0.845	-0.045	1.648
MAY 79	0.811	-0.085	1.468
AVERAGE	0.683	0.002	1.922

*Data not available for October 1978.

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 3.2.1-3 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 3.2.1-3 only because they form the references from which the error data given in the table are computed.

The data from Table 3.2.1-3 illustrates that for the Semco Macon 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 0.2 percent. For the curve derived from the laboratory single panel data, the error was 192.2 percent. Thus the long term collector array efficiency curve gives overwhelmingly better results than the curve derived from 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 can be 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 (December) and a typical summer month (June) operation. The actual midpoint which represents the average operating point for December is at 0.35 and for June at 0.27. Semco Macon 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 12 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 0.34 in June, 1978 to a minimum of 0.27 in December, 1978. On the average, the operational collector array efficiency exceeded the collector array efficiency, which included the effect of the control system, by 19 percent.

At Semco Macon, incident solar energy totaled 39.46 million Btu (Table 3.2.1-1) for the report period. Solar energy collected by the array totaled 10.32 million Btu, giving a collector array efficiency of 26 percent. Incident solar energy, during the time of collector loop operation, was 33.21 million Btu resulting in an operational collector efficiency of 31 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)

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

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

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 based on the eight months of valid data collected during the reporting period was 73 percent. Storage efficiency increases in proportion to system load, as observed for the period from December 1978 through April 1979, because of the increased utilization of solar energy to satisfy load demand rather than the dissipation of this energy in losses from the tank.

It should be noted that limitations in system instrumentation prohibited the accurate measurement of heat transfer losses from the wrap-around heat exchanger to the hot water storage tank. For the purpose of this analysis and, with MSFC concurrence, the heat transfer efficiency from the heat exchanger to the stored water was assumed to be 100 percent. This assumption results in the value of Collected Solar Energy (SECA) being equal to the solar energy component of Energy to Storage (STEI). The total Energy to Storage is then the sum of the solar energy component and energy from the electric auxiliary element.

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
May 78	1.64(1)	1.17	(4)	(4)	(4)
Jun 78	1.20(1)	0.81	(4)	(4)	(4)
Jul 78	1.40(1)	0.85(2)	(4)	(4)	(4)
Aug 78	1.38	0.88	0.03	0.65	126
Sep 78	1.30	0.88	0.02	0.67	125
Oct 78	1.65	1.08	0.01	0.66	126
Nov 78	0.85(1)	1.17(3)	(4)	(4)	(4)
Dec 78	2.01	1.59	-0.03	0.77	117
Jan 79	1.72	1.33	0.00	0.77	117
Feb 79	1.62	1.29	0.01	0.80	116
Mar 79	2.29	1.78	0.00	0.78	119
Apr 79	1.47	1.08	0.00	0.73	122
Total	18.53	13.89	0.04	--	--
Average	1.54	1.16	0.01	0.73	121

NOTES:

(1) Sum of solar energy collected and electric auxiliary energy. Solar energy collected is derived from product of incident solar energy and collector efficiencies of 26% for May, 27% for June, 28% for July and 25% for November.

(2) July system load derived from average loads for summer months (June, August and September)

(3) November system load derived from average loads for period from August 1978 through February 1979.

(4) Validity of data uncertain because of data system/transmission problems.

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 load consists of both solar energy and auxiliary thermal energy.

The performance of the Semco Macon Hot Water Subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in the 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 twelve month period from May 1978 through April 1979, the solar energy system supplied a total of 10.32 million Btu to the hot water subsystem load.

The total hot water subsystem load for this period was 13.91 million Btu and the average weighted monthly solar fraction (based on the eight months when this parameter could be reliably computed) was 50 percent.

The monthly average hot water load during the reporting period was 1.16 million Btu which is based on an average daily consumption of 72 gallons, delivered at an average temperature of 135°F and supplied from the city water mains at an average temperature of 73°F.

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Energy Supplied (Million Btu)				Hot Water Parameters			Standby Losses	Weighted** Solar Fraction (Percent)
	Auxiliary	Auxiliary* Thermal	Solar	Total	Gallons Used	Supply Temp (°F)	Load (Million Btu)	(Million Btu)	
May 78	0.80	0.80	0.84	1.64	2172	75	1.17(5)	0.47	(4)
Jun 78	0.44	0.44	0.76	1.20	(2200)[1]	(81)[2]	0.81(5)	0.39	(4)
Jul 78	0.40	0.40	1.00	1.40	(2200)[1]	(81)[2]	0.85(5)	0.55	(4)
Aug 78	0.37	0.37	1.01	1.38	2087	84	0.88	0.50	71
Sep 78	0.41	0.41	0.89	1.30	2022	84	0.88	0.42	67
Oct 78	0.46	0.46	1.19	1.65	2144	78	1.08	0.57	68
Nov 78	0.93	0.93	0.85	1.78	(2200)[1]	(70)[3]	1.17(5)	0.61	(4)
Dec 78	1.39	1.39	0.63	2.02	2564	69	1.59	0.43	30
Jan 79	1.07	1.07	0.65	1.72	2067	63	1.33	0.39	30
Feb 79	1.02	1.02	0.59	1.61	1972	62	1.29	0.32	31
Mar 79	1.23	1.23	1.06	2.29	2911	65	1.78	0.51	44
Apr 79	0.63	0.63	0.85	1.48	1862	69	1.08	0.40	55
Total	9.15	9.15	10.32	19.47	26400	--	13.91	5.56	--
Average	0.76	0.76	0.86	1.62	2200	73	1.16	0.46	50

NOTES:

1. Values are average of the nine "good data" months of reporting period.
2. Average of warm weather months (May, August and September).
3. Average of cold weather months (October, December and January).
4. No valid data available due to data system/transmission problems.
5. See notes on Table 3.1-1 for derivation of values.

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 Macon 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 Macon 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 May 1978 through April 1979 period, covered by this report, a total of 1.34 million Btu of operating energy was consumed. During the report period, a total of 10.32 million Btu of solar energy (Table 3.2.1-1) was supplied to the system load. Therefore, for every one million Btu of solar energy delivered to the load, 0.13 million Btu (38 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)
May 78	0.10	0	0.10
Jun 78	0.11	0	0.11
Jul 78	0.11	0	0.11
Aug 78	0.12	0	0.12
Sep 78	0.11	0	0.11
Oct 78	0.12	0	0.12
Nov 78	0.11	0	0.11
Dec 78	0.15	0	0.15
Jan 79	0.09	0	0.09
Feb 79	0.06	0	0.06
Mar 79	0.13	0	0.13
Apr 79	0.13	0	0.13
Total	1.34	0	1.34
Average	0.11	0	0.11

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 Macon 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 May 1978 through April 1979 are presented in Table 5-1. For this performance evaluation time period, the average hot water subsystem monthly savings were 0.86 million Btu. After the Energy Collection and Storage Subsystem (ECSS) operating energy was deducted, the average net monthly electrical savings were 0.75 million Btu or 219 kwh. For the overall time period covered by this report the total net savings were 8.98 million Btu or 2630 kwh.

TABLE 5-1

ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)	ECSS Operating Energy (Million Btu)	Net Savings Electrical	
	Hot Water		Million Btu	kwh
May 78	0.84(1)	0.10	0.74	217
Jun 78	0.76(1)	0.11	0.65	190
Jul 78	1.00(1)	0.11(2)	0.89	261
Aug 78	1.01	0.12	0.89	261
Sep 78	0.89	0.11	0.78	228
Oct 78	1.19	0.12	1.07	313
Nov 78	0.85	0.11(2)	0.74	217
Dec 78	0.63	0.15	0.48	141
Jan 79	0.65	0.09	0.56	164
Feb 79	0.59	0.06	0.53	155
Mar 79	1.06	0.13	0.93	272
Apr 79	0.85	0.13	0.72	211
Total	10.32	1.34	8.98	2630
Average	0.86	0.11	0.75	219

NOTES:

(1) Based on solar energy collected - See notes on Table 3.1-1.

(2) Data not available for July 1978 and November 1978. Total is extrapolated from 10-month average of ECSS operating energy.

6. MAINTENANCE

This section includes the solar energy system maintenance performed during the seasonal report period, May 1968 through April 1979. Maintenance data on the instrumentation system is not included in this report.

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

December 1978/January 1979 - Between December 4 and December 18, 1978 and again on January 13 and January 14, 1979 a control system anomaly occurred which caused the collector loop pump to operate at night, after useful solar energy collection had ended. This occasional circumstance resulted in an unintentional, active rejection of energy from storage that probably increased the use of auxiliary energy and expended some unnecessary collection loop pump operating energy. The problem was corrected by the solar system installation contractor and was not observed to recur subsequently.

7. SUMMARY AND CONCLUSIONS

For the report period May 1978 through April 1979, the average measured daily incident solar energy in the plane of the collector was 1343 Btu/ft^2 which was about 8 percent below the long-term value of 1456 Btu/ft^2. The average daily outdoor ambient temperature was 65°F which is exactly equal to the long-term average temperature. Consequently, weather conditions at the site had little adverse influence on system operation.

The incident solar energy for the 12-month period totaled 39.46 million Btu. Incident solar energy while the collector loop was operating was 33.21 million Btu and collected solar energy totaled 10.32 million Btu. This gives a collector operational efficiency of 31 percent. The 16 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. The wide discrepancy between predicted and measured collector performance when the prediction is based on the Florida Solar Energy Center test data, derated for the use of silicone oil has been discussed in Section 3.2.1.

Late in the spring of 1978, a series of design changes was completed at the Semco Macon Solar Energy Site to increase collector flow and improve system performance. The first monthly performance report published for the present system configuration was for May 1978 and the last for April 1979 which is the reporting period for this seasonal report.

Data transmission problems affected the data in the May 1978 through July 1978 time period and also in November 1978. Some performance data for this period were generated through the use of averaging or extrapolation techniques which are explained by notes on the appropriate data tables.

The average solar fraction during the reporting period was 50 percent (Table 3.1-1), based on the eight good data months when this performance factor could be computed. This compares favorably with the average solar fraction of 53 percent computed by the f-Chart analysis for the Semco Macon system.

Electrical energy savings at the site were a net total of 8.98 million Btu (2630 kwh) after the 1.34 million Btu (392 kwh) of operating energy required to operate the collector loop circulating pump were subtracted.

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.

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

- ELECTRICAL ENERGY SAVINGS (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.

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

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

- HOT WATER USED (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 MACON

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR SEMCO MACON

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

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

where $\bar{C}_p$ 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 Macon 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)

$= \Sigma\ [M100 \times CP35 \times (T101 - T100)] \times \Delta\tau$

WHERE CP35 IS THE SPECIFIC HEAT VALUE OF SILICONE OIL AS A FUNCTION OF TEMPERATURE

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

$= \Sigma\ [M100 \times CP35 \times (T101 - T100)/AREA] \times \Delta\tau$

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.)

$= 1/60\ \Sigma\ (I001 \times AREA) \times \Delta\tau$ 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 ELECTRICAL 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 THE 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-MACON                26.          LOCATION:  MACON        GA

ANALYST:    C. BOWEN                             FDRIVE NO.:   68.

COLLECTOR TILT:    42.70 (DEGREES)               COLLECTOR AZIMUTH:    0.0  (DEGREES)

LATITUDE:     32.70 (DEGREES)                    RUN DATE:  6/25/79


          *          *          *          *          *          *          *          *
 MONTH    *  HOBAR   *   HBAR   *   KBAR   *   RBAR   *   SBAR   *   HDD    *   CDD    *   TBAR
          *          *          *          *          *          *          *          *
**********************************************************************************************
          *          *          *          *          *          *          *          *
JAN       *   1714.  *   771.   * 0.44952  *  1.510   *  1164.   *    543   *     10   *    48.
FEB       *   2142.  *  1021.   * 0.47680  *  1.324   *  1352.   *    423   *     14   *    50.
MAR       *   2664.  *  1364.   * 0.51207  *  1.129   *  1540.   *    298   *     35   *    57.
APR       *   3168.  *  1737.   * 0.54825  *  0.951   *  1651.   *     66   *     90   *    66.
MAY       *   3490.  *  1884.   * 0.53985  *  0.834   *  1572.   *      6   *    269   *    74.
JUN       *   3609.  *  1921.   * 0.53225  *  0.788   *  1514.   *      0   *    438   *    80.
JUL       *   3541.  *  1785.   * 0.50391  *  0.811   *  1448.   *      0   *    508   *    81.
AUG       *   3284.  *  1718.   * 0.52326  *  0.697   *  1542.   *      0   *    493   *    81.
SEP       *   2840.  *  1438.   * 0.50633  *  1.050   *  1510.   *      0   *    324   *    76.
OCT       *   2291.  *  1246.   * 0.54407  *  1.283   *  1599.   *     82   *    103   *    66.
NOV       *   1812.  *   940.   * 0.51888  *  1.509   *  1419.   *    304   *     10   *    55.
DEC       *   1592.  *   730.   * 0.45847  *  1.587   *  1159.   *    518   *      0   *    48.
          *          *          *          *          *          *          *          *


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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