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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL
REPORT FOR SOLARON-DUFFIELD, DUFFIELD, VIRGINIA

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For the U. S. Department of Energy



(NASA-CR-161507) SOLAR ENERGY SYSTEM
PERFORMANCE EVALUATION REPORT FOR
SOLARON-DUFFIELD, DUFFIELD, VIRGINIA
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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 the payback performance based on life cycle costs for the same solar system in various geographic regions. Another document specifically related to this system is Reference [1].*

*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The Solaron Duffield Solar Energy System was designed to provide both space heating and domestic hot water (DHW) preheating for a two story single-family residence containing approximately 1940 square feet in Duffield, Virginia. Solar energy collection is accomplished with flat-plate collectors using air as the transport fluid. The collector array has a gross area of 429 square feet and faces south at an angle of 40 degrees from the horizontal. Solar energy is stored in a 265 cubic foot rock thermal storage bin located on the lower level of the house. Solar energy is transferred to the DHW subsystem by means of an in-duct heat exchanger (HX1) whenever the system is storing collected solar energy. Water from the 80 gallon preheat tank is transferred to the 52 gallon DHW tank when there is a demand for hot water. The auxiliary space heating subsystem consists of an air to liquid heat pump coupled with a 1000 gallon water storage tank. The heat pump can provide energy either directly to the house or to the 1000 gallon tank. The system is designed so that the heat pump can charge the 1000 gallon tank during off-peak hours when electrical rates are lower. The heat pump with the off-peak storage can also be used for cooling. Energy stored in the tank can then be used for space heating purposes as required. Auxiliary energy for both the space heating and DHW subsystems is provided by electricity. The heat pump has a nominal capacity of 30,000 Btu/Hr with supplemental heat strips rated at 12 kw, and the auxiliary hot water heater is rated at 4.5 kw. The system is shown schematically in Figure 2-1, and sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 [2]. The measurement symbol prefixes: W, T, EP, and I represent respectively: flow rate, temperature, electric power, and insolation. The system has the following modes of operation:

A. First Stage

1. Collector to Storage and DHW. In this mode the collector blower transfers solar energy from the collector array to the rock thermal storage bin through the DHW heat exchanger. Part of the solar energy is utilized in the DHW preheat loop and the remaining solar energy is delivered to storage. This mode is entered

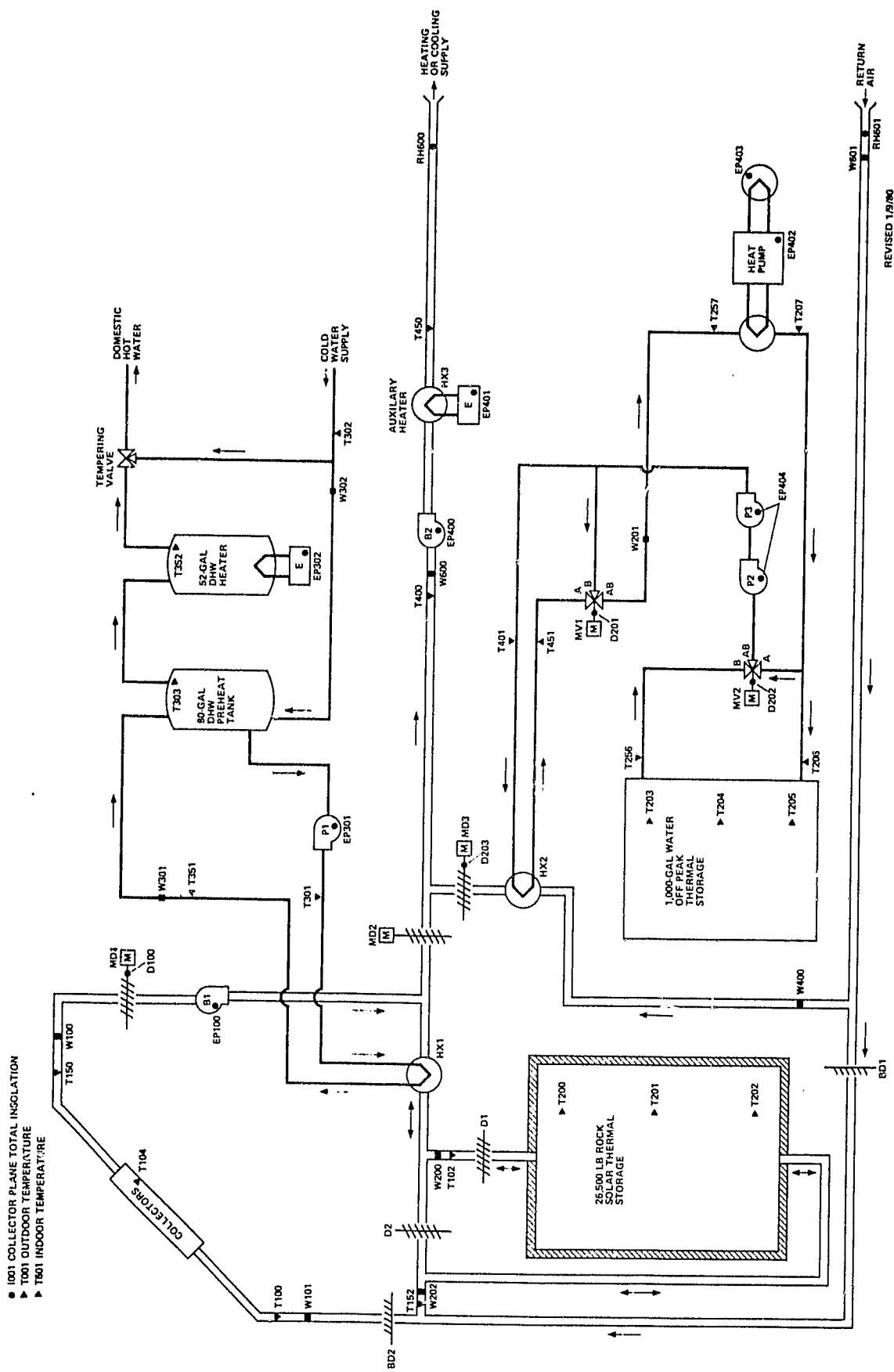


Figure 2-1 Solaron Duffield Solar Energy System Schematic

whenever the differential temperature between the collectors and the return air duct is $40 \pm 7^{\circ}\text{F}$ and heating demands are such that direct space heating from the collector array is not required. This mode terminates whenever the differential temperature falls to $25 \pm 5^{\circ}\text{F}$, or less, or direct space heating from the collector array is required.

2. Collector to Space Heating Load. In this mode dampers MD1 and MD2 are open and solar energy goes directly to the residential area utilizing both the collector and circulating blowers. The DHW heat exchanger is bypassed in this mode and all collected energy is delivered to the space heating load. The same differential temperature conditions described above also control operation in this mode.
3. Storage to Load. When incident solar energy on the collector array is insufficient, space heating is provided from the storage bin by way of the circulating blower. Dampers MD1 and MD3 are closed in this mode and MD2 is open. A minimum storage temperature of 90°F is required for operation in this mode.

B. Second Stage

4. Heat Pump Auxiliary Direct. When insufficient solar energy is present on the collector array and the storage temperature is also insufficient to maintain a level of comfort, dampers MD1 and MD2 close and MD3 opens to provide heated air from the heat pump by way of the auxiliary heating/cooling heat exchanger. At outdoor temperatures of approximately 40°F or above, the heat pump will carry the entire space heating load. For temperatures between 2°F and approximately 40°F , the heat pump is supplemented by the electrical strip heaters.

It is also possible to heat in this mode while, at the same time, collected solar energy is being delivered to storage. This

condition exists whenever the room thermostat is calling for second stage heating and sufficient insolation is available to allow the collector array to operate.

5. Auxiliary Heat from Heat Pump Storage. This mode allows space heating from the off-peak water storage tank. During off-peak hours, when the heat pump is not needed to heat the residence, it stores hot water for use during this mode. Dampers MD1 and MD2 are closed and MD3 is open in this mode.

C. Third Stage

6. Electrical resistance (strip) heat is used whenever the heat pump is unable to maintain the desired comfort level in the house. Above 2°F the strips supplement the heat pump, as described in Mode 4 above, and below 2°F the strips carry the entire load.

2.1 Typical System Operation

Curves depicting typical system operation on a cold, mostly bright day (February 3, 1980) are presented in Figure 2.1-1. Figure 2.1-1 (a) shows the insolation on the collector array and the period when the array was operating (shaded area). Also shown in Figure 2.1-1 (a) are the collector array temperature profiles. These are the inlet temperature (T100), the outlet temperature (T150) and the absorber plate temperature (T104).

On this particular day the collector array began operating at 0938 hours. At that time the insolation level was $178 \text{ Btu/Ft}^2\text{-Hr}$ and the absorber plate temperature (T104) was 99°F . At the same time the collector array inlet temperature (T100) was 52°F .

The collector array operated normally throughout the day. It will be noted that T104 tracked the insolation level quite closely during the operational period. The array outlet temperature (T150) also tracked both the insolation level and absorber plate temperature but its fluctuations were not as pronounced as those of the absorber plate temperature. The collector array inlet temperature (T100) showed a gradual rise almost constantly during the operational period. This is expected because the system was operating in the collector to storage and hot water mode most of the day. As a result T100 tended to track the temperature at the bottom of the storage bin fairly closely. The system ran until 1529 hours and then shut down for the day.

Figure 2.1-1 (b) presents a profile of the storage bin temperatures for the selected day. The system operated all day in either the collector to space heating mode or collector to storage and DHW preheating modes, depending on space heating demand. During the charging period the temperature profile in the storage bin behaved as would be expected, based on the air flow pattern through the storage bin and collector array outlet temperature (T150). Once

February 3, 1980

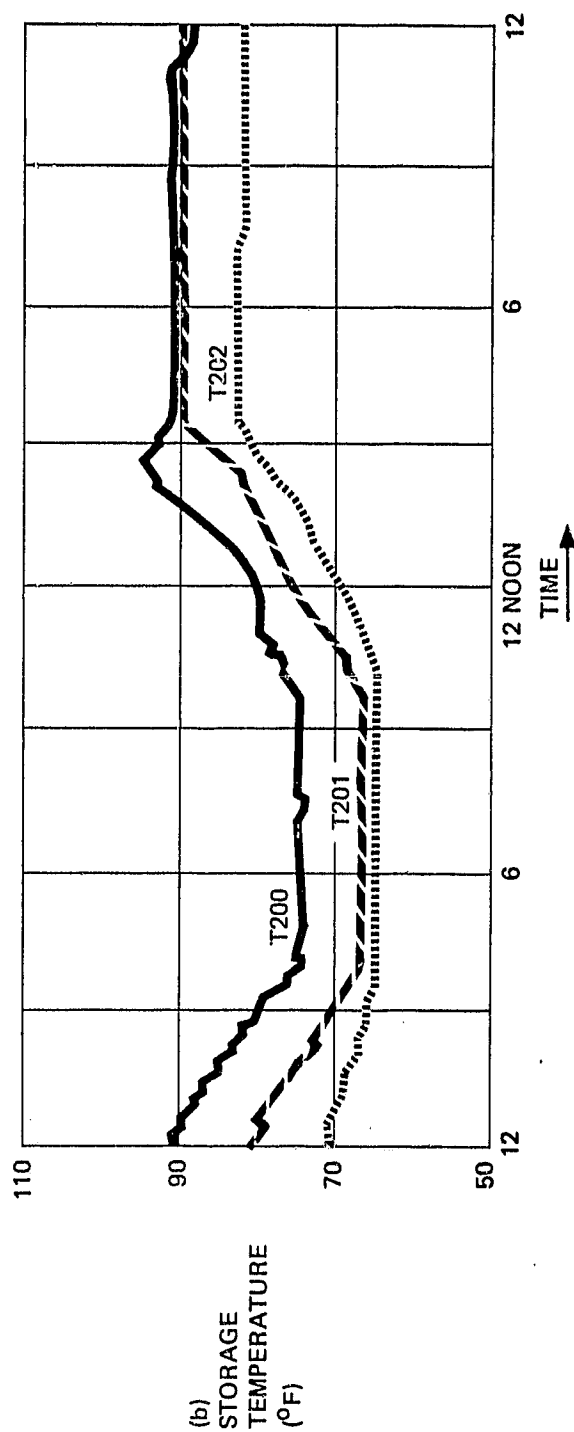
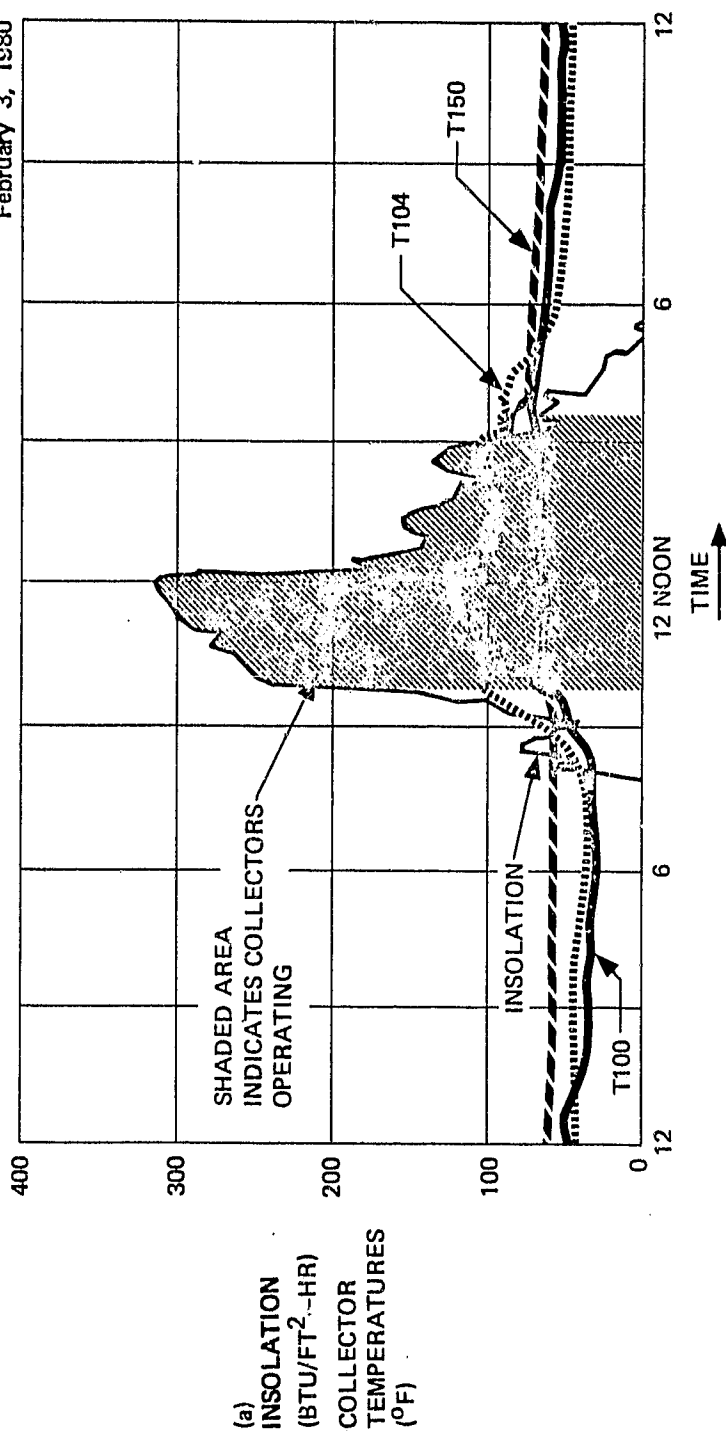


Figure 2.1-1 Typical System Operating Parameters

collector array operation, and hence storage charging, ceased, the system remained relatively stable for the rest of the day, as the system did not enter the storage to space heating mode during the evening hours.

2.2 System Operating Sequence

Figure 2.2-1 presents bar charts showing typical system operating sequences for February 3, 1980. This data correlates with the curves presented in Figure 2.1-1 and provides some additional insight into those curves. This particular day was chosen because almost all possible modes of system operation were exercised at some time during the day.

At the beginning of the day the system was operating intermittently in the rock storage to space heating mode and in the off-peak to storage mode. Operation continued in these modes until 0349, at which time the heat in rock storage was depleted and the system switched to the heat pump to space heating mode. Operation continued in this mode until 0749 hours, except for three short periods when the heat pump went into its defrost cycle and the heat strips came on. There was one brief period when the space heating demand was satisfied and the system switched briefly back to the off-peak to storage mode. The system operated in the off-peak to space heating mode until 0942 hours. At this time the collectors were operating and the system operated intermittently between the collector to space heating mode and the collector to storage and DHW preheating mode. At 1537 hours the system changed over to the heat pump to space heating mode and after 2210 hours operated intermittently between the heat pump to space heating mode and the heat pump to off-peak storage mode.

Domestic hot water usage for this day was considerably above the 61 gallons per day average for February. As shown in Figure 2.2-1, approximately 101 gallons of water was used during the day. Therefore, a higher than normal amount of auxiliary energy was required to support the DHW subsystem.

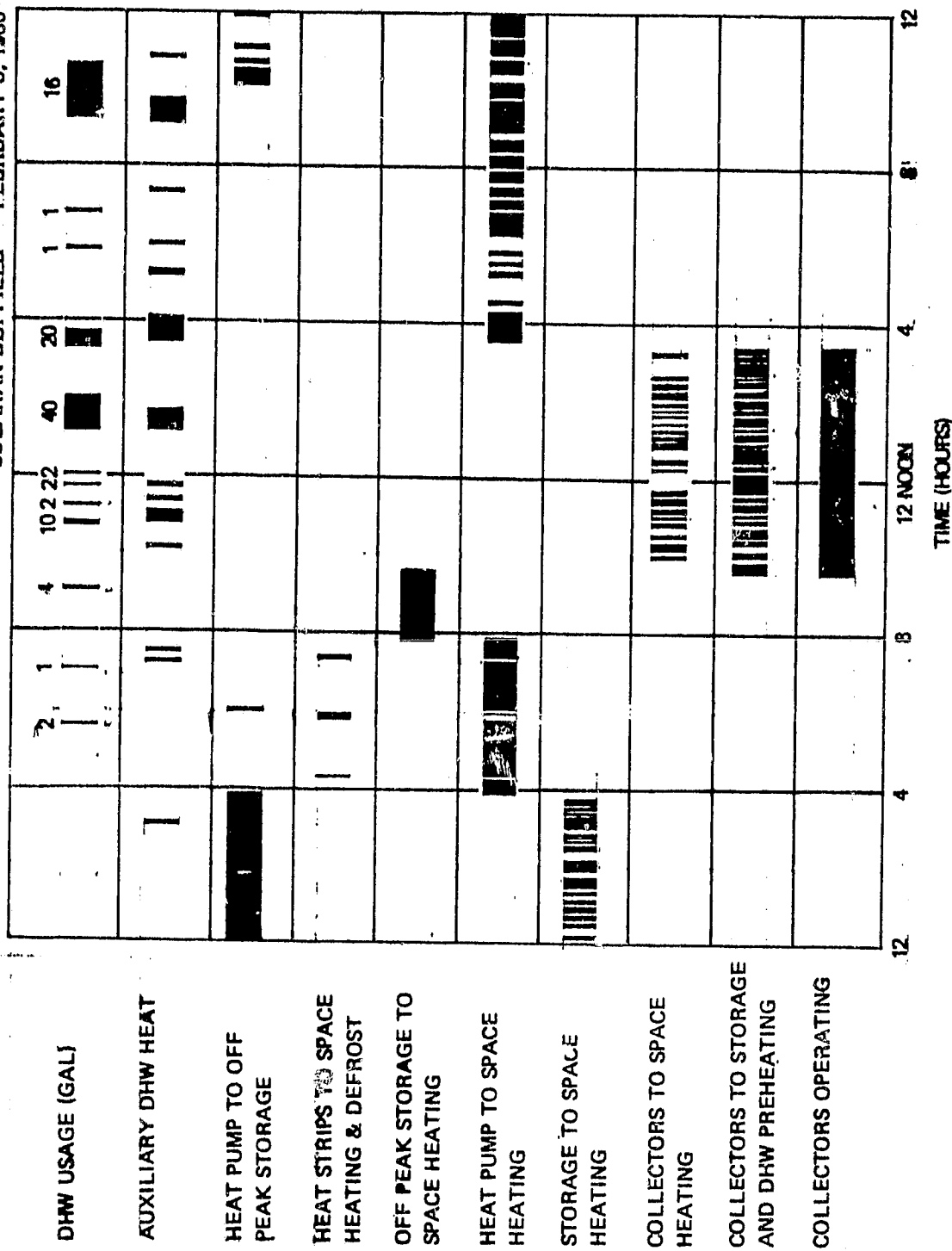


Figure 2.2-1 Typical System Operating Sequence

3. PERFORMANCE ASSESSMENT

The performance of the Solaron Duffield Solar Energy System has been evaluated for the October 9, 1979 through March 1980 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.

For the purposes of this Solar Energy System Performance Evaluation, monthly performance data were regenerated to reflect refinements and improvements in the system performance equations that were incorporated as the analysis period progressed. These modifications resulted in changes in the numerical values of some of the performance factors. However, the basic trends have not been affected.

Before beginning the discussion of actual solar energy system performance some highlights and pertinent information relating to site history are presented in the following paragraphs.

The Solaron Duffield Solar Energy System was initially activated in August 1979. At that time all known system problems were addressed and corrected where possible. After the system was started up, a period of data monitoring was initiated to verify that the solar system and monitoring instrumentation were functioning properly.

During the initial check-out phase there were several problems identified relating to both the solar energy system and the monitoring instrumentation.

Some of the more significant problems were: the heat pump operated in the cooling mode, but the compressor did not operate, flow imbalances throughout the system; and a significant amount of collector array leakage.

These problems, with the exception of the collector array leakage, were all corrected before the system entered the reporting phase in October 1979. The collector array leakage problem was accepted because it would have been very difficult (and costly) to correct it.

Once the system entered the reporting period there were very few instrumentation problems noted. However, control problems, especially with the off-peak heating system, were noted throughout the reporting period. These problems, where applicable, have been addressed in the appropriate subsections.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the Solaron Duffield Solar Energy system located in Duffield, Virginia. This analysis was conducted by evaluation of measured system performance against the expected performance 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" [2]. The performance of the major subsystems is also evaluated in subsequent sections of this report.

The measurement data were collected for the period October 1979 through March 1980. 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 given 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:

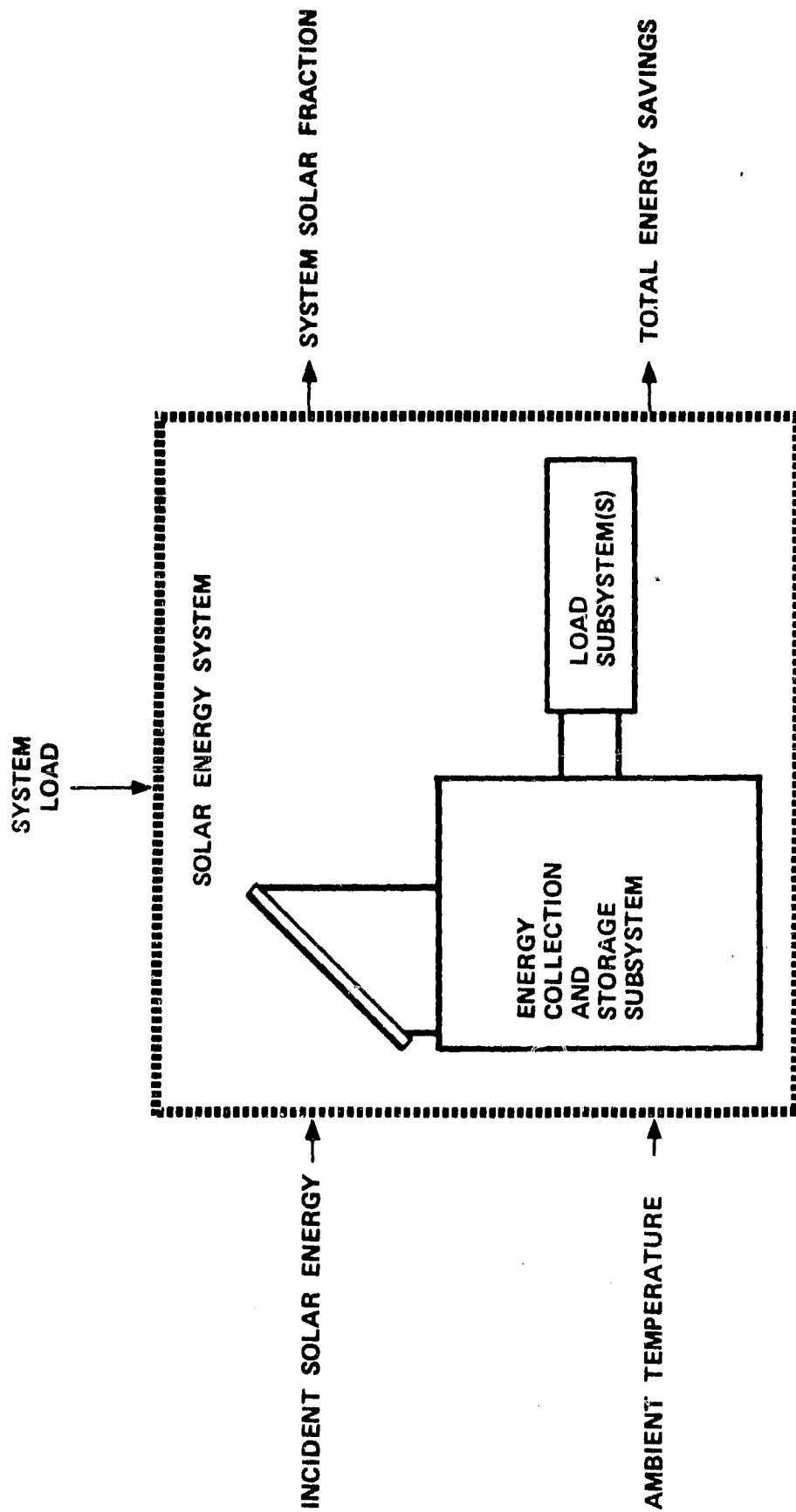


Figure 3.1.1 Solar Energy System Evaluation Block Diagram

Inputs

- Incident solar energy - The total solar energy incident on the collector array and 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 purposes. The long-term data are taken from Reference 1 of Appendix C. However, the long-term data had to be based on actual data for Knoxville, Tennessee and Roanoke, Virginia, as there were no long-term data available for the Duffield, Virginia area. Appropriate weighting was applied to the Knoxville and Roanoke data to derive an estimate of the long-term conditions at Duffield.

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

TABLE 3.3-1

SYSTEM PERFORMANCE SUMMARY

Month	Daily Incident Solar Energy Per Unit Area (40° Tilt) (Btu/Ft ² -Day)		Ambient Temperature (°F)		System Load - Measured (Million Btu)	Solar Fraction (Percent)		Total Energy Savings (Million Btu)
	Measured	Long-Term Average	Measured	Long-Term Average		Measured	Expected	
Oct 79	537	1,461	52	60	5.02	36	12	1.53
Nov 79	895	1,184	46	48	9.72	63	43	4.24
Dec 79	1,037	952	36	40	11.55	37	27	2.95
Jan 80	457	1,012	39	39	10.30	11	4	0.83
Feb 80	956	1,210	31	41	12.06	47	24	3.69
Mar 80	873	1,421	42	48	8.97	42	26	2.91
Total	--	--	--	--	57.62	--	--	16.15
Average	793	1,207	41	46	9.60	39	24	2.69

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 Solaron Duffield site for the six month report period, the long-term average daily incident solar energy in the plane of the collector array was 1,207 Btu/Ft². The average daily measured value was 793 Btu/Ft², which is about 34 percent below the long-term value. On a monthly basis, October of 1979 was the worst month with an average daily measured value of incident solar energy 63 percent below the long-term average daily value. December 1979 was the best month with an average daily measured value nine percent above the long-term average daily value.

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 for the six month period from October 1979 through March 1980 was 46°F at the Solaron Duffield site. This was 12 percent above the measured value of 41°F.

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 [7]). The model used in the analysis is based on manufacturers' data and other known system parameters. The basis for the model is a set of 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. As shown in Table 3.1-1, the measured system solar fraction of 39 percent did not compare closely with the expected value of 24 percent generated by the modified f-Chart program. The modified f-chart simulation used for Seasonal Report Analysis with system losses approximated is not a good prediction of the performance of the Solaron Duffield installation. The reasons for this are under investigation.

The total energy savings is the most important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with less expensive 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 computed energy savings for the Solaron Duffield Solar Energy System was 16.15 million Btu, or 4,731 kWh, which was not a large amount of energy. However, this savings is based only on measured inputs of solar energy to the load subsystems. At the Solaron Duffield site there were a significant amount of uncontrolled (and hence unmeasured) inputs of solar energy into the house. These uncontrolled inputs of solar energy came primarily from storage and transport losses and tended to reduce the overall heating load, which in turn tended to increase real savings. This situation is addressed in more detail in the appropriate sections that follow.

3.2 Subsystem Performance

The Solaron Duffield Solar Energy Installation may be divided into four subsystems:

1. Collector array
2. Storage
3. Hot water
4. Space heating

Each subsystem has been evaluated by the techniques defined in Section 3 and is numerically analyzed each month for the monthly performance assessment. This section presents the results of integrating the monthly data available on the four subsystems for the period October 1979 through March 1980.

3.2.1 Collector Array Subsystem

The Solaron Duffield collector array consists of 22 Solaron 2000 series flat-plate air collectors arranged in two parallel rows of 11 collectors each. These collectors are a one-pass air heating type with a double glazing. Typical flowrate through the collector array is approximately 3.01 CFM per square foot of gross array area. Details of the air flow path are shown in Figure 3.2.1-1 (a) and a photograph of the collector array installation is presented in Figure 3.2.1-1 (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 must be used in determining collector array efficiency. The efficiency is then expressed by the equation:

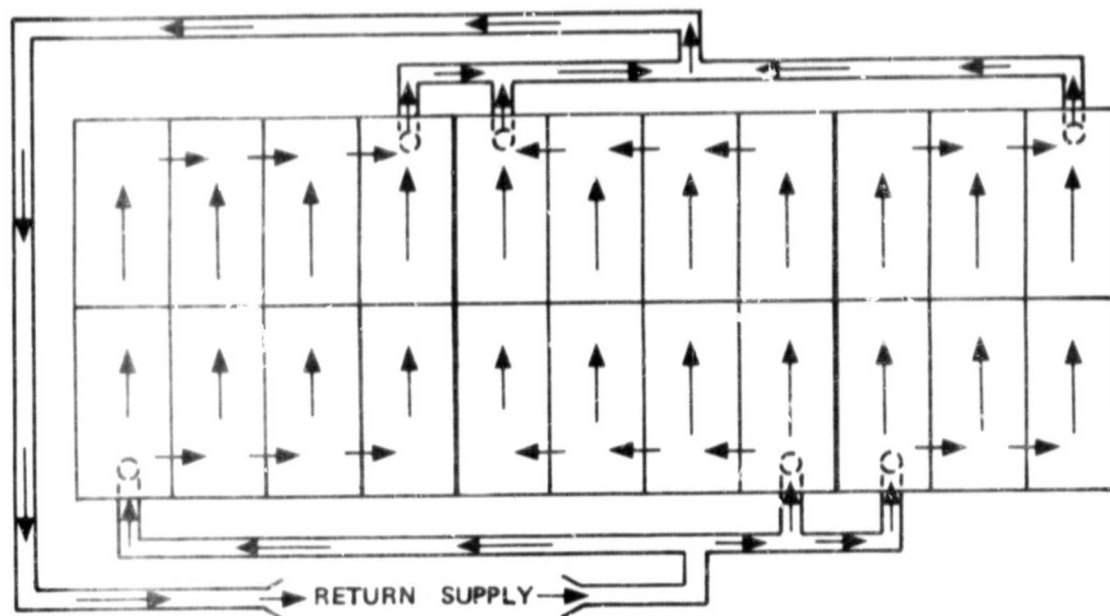
$$\eta_c = Q_s / Q_i \quad (1)$$

where η_c = Collector array efficiency

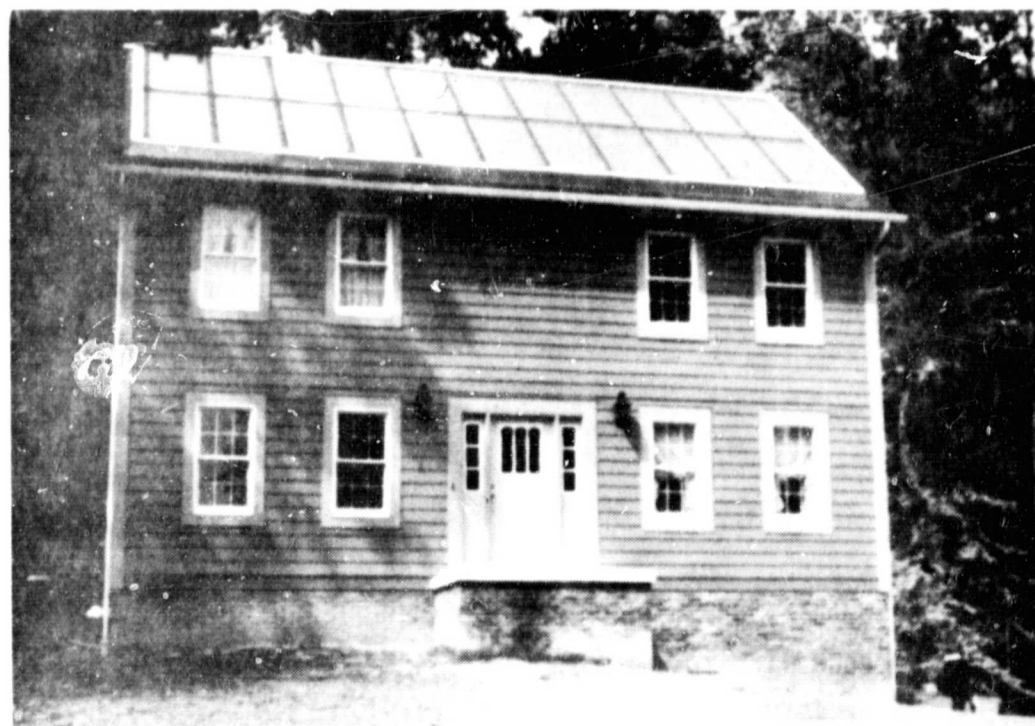
Q_s = Collected solar energy

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.



(a) Collector Air Flow Path



(b) Collector Array Installation

COLLECTOR ARRAY

Tilt Angle - 40°
Azimuth - Due South

SITE LOCATION

Latitude - 36.48°N
Longitude - 82.40°W

Figure 3.2.1-1 Collector Details

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 79	7.14	2.64	0.37	4.01	0.66
Nov 79	11.52	4.37	0.38	8.31	0.53
Dec 79	13.80	5.38	0.39	10.31	0.52
Jan 80	6.07	1.51	0.25	2.88	0.52
Feb 80	11.89	5.17	0.43	8.85	0.58
Mar 80	11.61	4.38	0.38	8.34	0.53
Total	62.03	23.45	--	42.70	--
Average	10.34	3.91	0.38	7.12	0.55

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 [4] 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 the collectors. The collector evaluation performed for this report using the field data indicates that there was some difference between the laboratory single panel collector data and the collector data determined from long-term field measurements. This may or may not always be 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.). It is to be noted that the performance of air collectors is particularly sensitive to the air flow rate with higher efficiencies being achieved by increases in the air flow rate through the collectors.
- 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 long-term data base for Solaron Duffield includes only the months of November 1979, December 1979 and February 1980. Although the system was operating during the other three months of the report period the data was not included in the long-term base. In October 1979 data was only available for 12 days during the month. In both January and March of 1980 the data had too much scatter to provide any useful input to the long-term data base. Therefore, the long-term data base had to be constructed from the three months when good data was available.

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.

*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.

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 fluid 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:

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

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 ratio A_p/A_a is assumed to be unity for this analysis.

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

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

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:

$$b = F_R(\tau\alpha) \quad (6)$$

and

$$m = F_R U_L$$

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 long-term first order curve presented in Figure 3.2.1-2 indicates that the collector array as a whole seemed to perform better than the laboratory test unit. However, this is probably due to the fact that the performance equations for the collector array take into account the leakage of outside ambient air into the array. Also the long-term first order curve has a slightly less negative slope than the curve derived from single panel laboratory test data. This is attributable to lower losses (other than leakage) resulting from array effects. In addition it should be noted that the operational collector efficiency values presented in Table 3.2.1-1 are high as compared to the long-term efficiency curve. This is probably due to the fact that the collector array normally operates one to two hours outside of the time period covered by the detailed collector analysis (sun angle within 30 degrees of the collector normal). During these early morning and late afternoon hours, but especially during the late afternoon, the leakage of outside ambient air into the collector array tends to raise the collector array efficiency a significant amount above the mid-day efficiency. Since the ambient air leakage is accounted for in all the efficiency calculations, the values reported in Table 3.2.1-1 can be higher than would be expected based on the long-term analysis alone. The laboratory predicted instantaneous efficiency is not in close agreement with the curve derived from actual field operation. This indicates that the laboratory derived curve might not be useful for design purposes in an array configuration of this type. However, this statement must be tempered by the fact that actual performance might approach predicted performance more closely if there were no leakage problems with the collector array or ductwork.

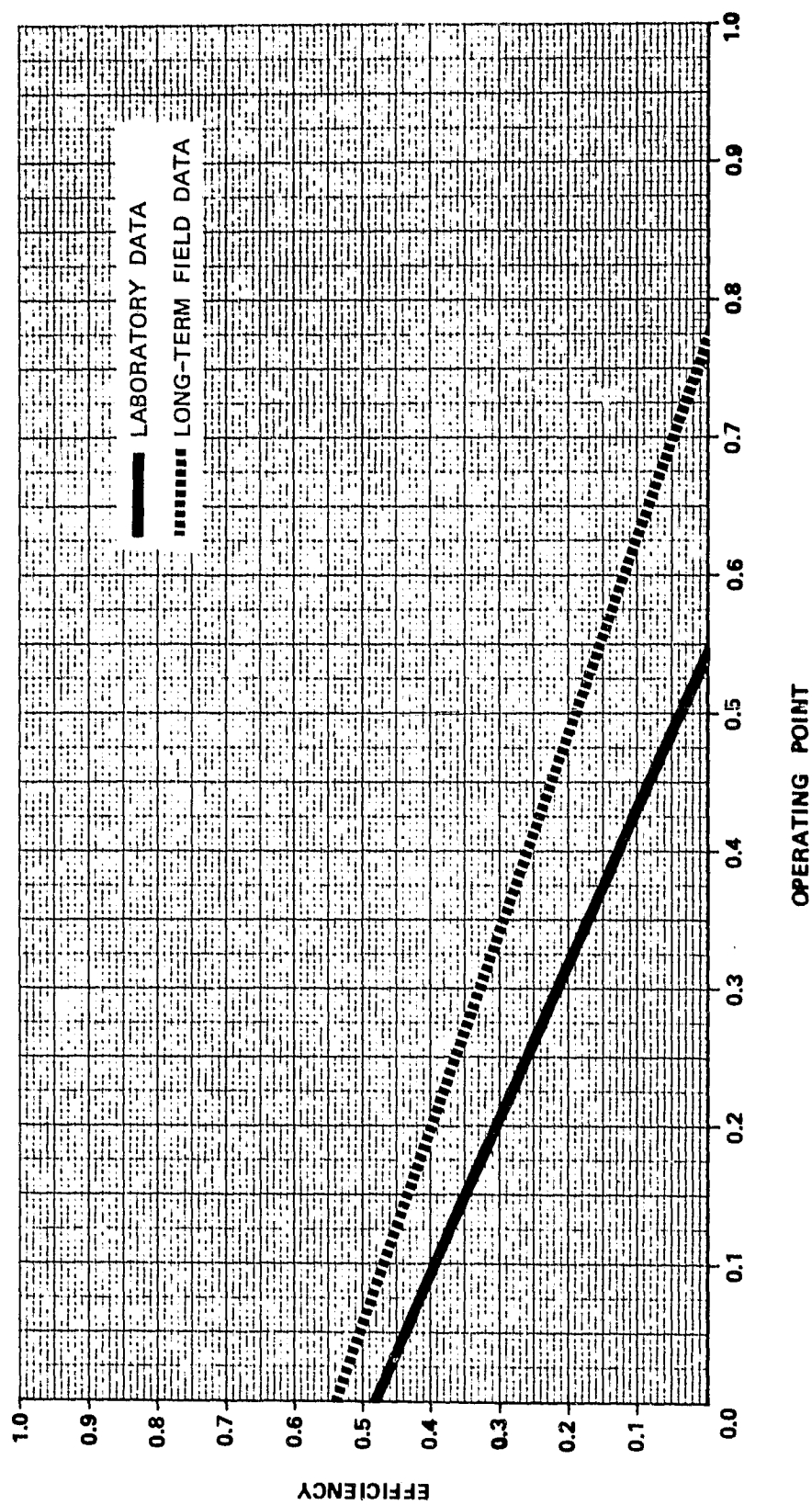


Figure 3.2.1-2 Solaron Duffield Collector Efficiency Curves

For information purposes the data associated with Figure 3.2.1-2 is as follows:

Single panel laboratory data

$$F_R(\tau\alpha) = 0.476$$

$$F_R U_L = -0.856$$

Long-term field data

$$F_R(\tau\alpha) = 0.536$$

$$F_R U_L = -0.693$$

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.

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: SOLARON DUFFIELD DUFFIELD, VIRGINIA

Month	Collected Solar Energy (Million Btu)	Error	
		Field Derived Long-Term	Laboratory Single Panel
Nov 79	3.840	0.103	0.288
Dec 79	4.053	0.106	0.315
Feb 80	4.650	0.233	0.535
Average	4.181	0.139	0.388

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:

$$\text{Error} = (A-P)/P \quad (7)$$

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 either to differences in the data base or to the differences in data processing between the software programs used to generate the monthly performance assessment 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 Solaron Duffield 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 13.9 percent. For the curve derived from the laboratory single panel data, the error was 38.8 percent. Thus the long-term collector array efficiency curve gives significantly better results than the 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 then 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, the climatic factors of the site, i.e., incident solar energy and ambient temperature, and the method of system operation. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (February) and a typical transitional month (November) operation. The approximate average operating point for February is at 0.16 and for November 0.08. In terms of Equation (3) it can be seen that, as the operating point becomes larger, the collector array efficiency decreases.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the six month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equations (1) and (2). On the average the operational collector array efficiency exceeded the collector array efficiency, which included the affect of the control system, by 45 percent.

Additional information concerning collector array analysis in general may be found in Reference [6]. 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.

SOLARON DUFFIELD DUFFIELD, VA
COLLECTOR TYPE: SOLARON COLLECTOR MODEL: 2000 SERIES

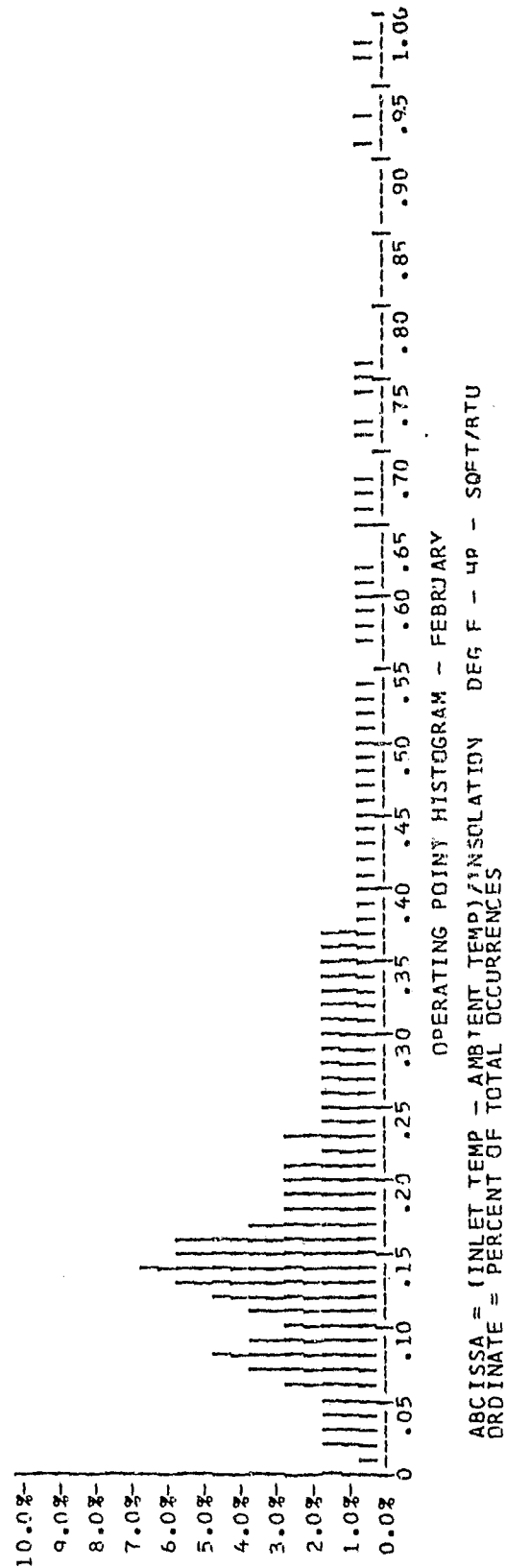
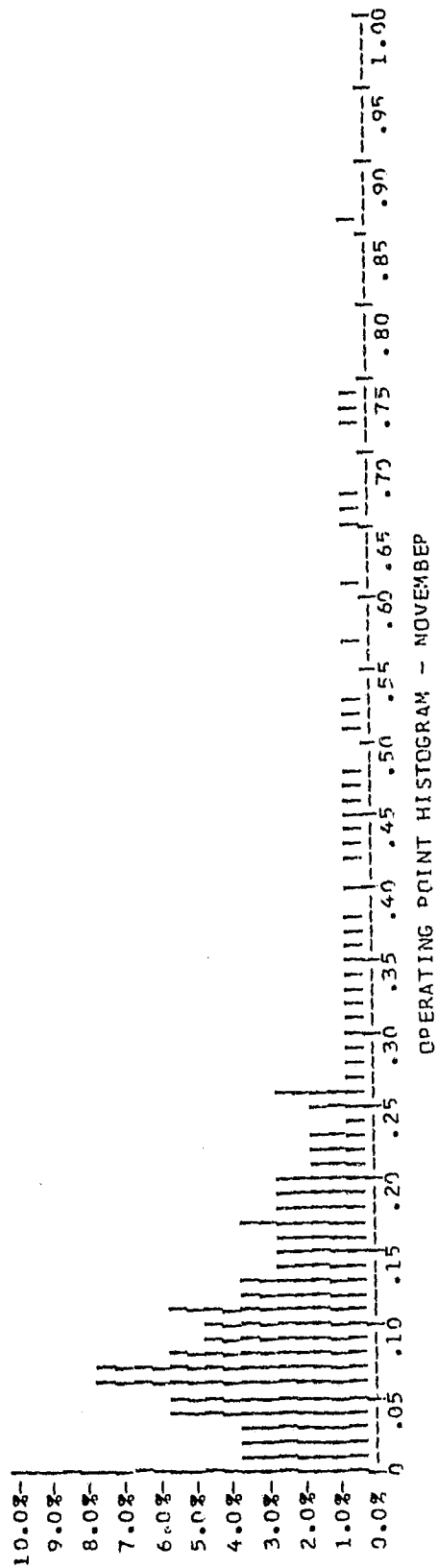


Figure 3.2.1-3 Solaron Duffield Operating Point Histograms for
Typical Winter and Transitional Months

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

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \quad (8)$$

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 can be illustrated in the following discussion.

Table 3.2.2-1 summarizes the storage subsystem performance during the report period.

During the six month period an approximate total of 16.56 million Btu was delivered to storage and 16.43 million Btu were extracted for support of the space heating load. During this period the net change in stored energy was 0.05 million Btu, which leads to an overall storage efficiency of 0.96 and a total heat loss from storage of 0.08 million Btu. The average temperature of storage was 80°F.

It will be noted that during the month of November considerably more heat was removed from storage than was put into storage. This was brought about by a damper malfunction which caused the house return air to pass through storage when the system was operating in the auxiliary heating mode. Thus the auxiliary heating system was adding heat to storage.

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 79	2.11	1.28	0.18	0.69	77
Nov 79	2.66	4.93	-0.17	1.79*	87
Dec 79	3.67	3.25	0.01	0.90	77
Jan 80	1.00	0.71	-0.05	0.65	77
Feb 80	3.59	3.26	-0.03	0.90	79
Mar 80	3.59	3.00	0.01	0.84	83
Total	16.56	16.43	0.05	--	--
Average	2.76	2.74	-0.01	0.96	80

*This number is greater than 1.00 due to the damper leakage problem discussed in the text.

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 Solaron Duffield hot water subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in Table 3.2.3-1 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. It does not represent the ratio of solar energy supplied to the sum of solar plus auxiliary thermal energy supplied shown in the Table.

For the six month period from October 1979 through March 1980, the solar energy system supplied a total of 2.90 million Btu to the hot water subsystem. However, the hot water subsystem itself effectively delivered 1.93 million Btu to the hot water load. The difference represents losses attributable to the preheat tank and its associated plumbing. The total hot water load for this period was 5.71 million Btu, and the weighted average monthly solar fraction was 28 percent.

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Hot Water Parameters				Energy Consumed (Million Btu)			Weighted Solar Fraction (Percent)
	Load (Million Btu)	Gallons Used	Temperatures (°F)		Solar	Auxiliary Thermal	Auxiliary	
			Supply	Delivery				
Oct 79	0.67	1,379	66	128	0.38	0.73	0.73	26
Nov 79	0.73	1,379	62	126	0.51	0.72	0.72	31
Dec 79	1.02	1,914	56	126	0.57	1.00	1.00	27
Jan 80	1.05	1,817	53	125	0.23	1.18	1.18	15
Feb 80	1.08	1,763	50	125	0.62	0.94	0.94	33
Mar 80	1.16	1,922	52	125	0.59	1.01	1.01	34
Total	5.71	10,174	--	--	2.90	5.58	5.58	--
Average	0.95	1,696	57	126	0.48	0.93	0.93	28

The monthly average hot water load during the reporting period was 0.95 million Btu. This is based on an average daily consumption of 56 gallons, delivered at an average temperature of 125°F and supplied to the system at an average temperature of 57°F. The temperature of the supply water ranged from a low of 50°F in February to a high of 66°F in October.

Each month an average of 0.32 million Btu of solar energy from the preheat tank and 0.93 million Btu of auxiliary thermal (electrical) energy were supplied to support the hot water load. Since the average monthly hot water load was 0.95 million Btu, an average of 0.30 million Btu was lost from the hot water tank each month. In addition, an average of 0.02 million Btu of operating energy was required to support the hot water subsystem each month.

3.2.4 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy.

The performance of the Solaron Duffield space heating subsystem is presented in Table 3.2.4-1. For the six month period from October 1979 through March 1980, the solar energy system supplied a measured total of 20.22 million Btu to the space heating load. The total measured heating load for this period was 51.91 million Btu, and the average monthly solar fraction was 39 percent.

During the six month reporting period a total of 16.55 million Btu of auxiliary energy was consumed by the space heating subsystem when it was operating in the various auxiliary heating modes. Of this total, 13.81 million Btu were consumed by the heat pump compressor and 2.74 million Btu were consumed by the heat strips. Since 44.61 million Btu were added to the auxiliary heating system by the heat pump, the average COP of the heat pump was approximately 3.23. This is in contrast to the average COP of approximately 1.63 for the entire off-peak system. The average overall system COP of 1.63 is based on a comparison of the total amount of power consumed by the heat pump compressor and pump P2 versus the total energy delivered to the auxiliary system at HX2 (reference Figure 2-1). As such, it is a more accurate indicator of the auxiliary heat pump system performance because it represents the actual ratio of energy sought to energy that costs. Power unnecessarily consumed by either pumps P2 and P3 or the heat pump compressor due to control system or other problems is included, so the average system COP represents all phases of system operation.

TABLE 3.2.4-1
HEATING SUBSYSTEM PERFORMANCE

	Heating Parameters				Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
	Load (Million Btu)	Temperatures (°F)		Solar	Auxiliary Thermal	Auxiliary		
		Building	Outdoor					
Month								
Oct 79	4.35	73	52	1.65	6.20	2.28	38	
Nov 79	9.00	73	46	5.93	4.90	2.30	66	
Dec 79	10.53	73	36	3.99	9.11	3.39	38	
Jan 80	9.25	73	39	1.00	11.20	3.60	11	
Feb 80	10.97	72	31	4.29	9.02	3.05	39	
Mar 80	7.81	72	42	3.36	6.92	1.93	43	
Total	51.91	--	--	20.22	47.35	16.55	--	
Average	8.65	73	41	3.37	7.89	2.76	39*	

*Average solar fraction is the ratio of total solar energy to total load.

4. OPERATING ENERGY

Operating energy for the Solaron Duffield Solar Energy System is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy, hot water subsystem operating energy and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Table 4-1.

Total system operating energy for the Solaron Duffield Solar Energy System is that electrical energy required to operate the blowers in the ECSS loop (B1) and the air distribution duct (B2), the pumps in the DHW subsystem (P1) and the auxiliary heat pump system (P2 and P3), and the heat pump outside fan. These are shown as EP100, EP400, EP301, EP404 and EP403, respectively, in Figure 2-1. Although additional electrical energy is required to operate the three motor driven dampers and the control system for the installation, it is not included in this report. These devices are not monitored for power consumption and the power they consume is inconsequential when compared to the fan and pump motors.

During the six month reporting period, a total of 11.58 million Btu (3393 kWh) of operating energy was consumed. However, this includes the energy required to operate the blower in the air distribution duct and the pump and outside fan in the heat pump system, and that energy would be required whether or not the solar energy system was being utilized for space heating. Therefore, the energy consumed by these devices is not considered to be solar peculiar operating energy, even though it is included as part of the space heating subsystem operating energy.

TABLE 4-1
OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Hot Water Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Oct 79	0.080	0.019	1.549	1.648
Nov 79	0.104	0.028	0.629	0.761
Dec 79	0.120	0.028	2.111	2.259
Jan 80	0.040	0.009	2.512	2.561
Feb 80	0.112	0.024	2.263	2.399
Mar 80	0.096	0.024	1.828	1.948
Total	0.552	0.132	10.892	11.576
Average	0.092	0.022	1.815	1.929

A total of 0.68 million Btu (199 kWh) of operating energy was required to support the pump and fan that are unique to the solar energy system during the reporting period. Of this total, 0.55 million Btu were allocated to the Energy Collection and Storage Subsystem (ECSS) and 0.13 million Btu were allocated to the DHW Subsystem. Since a measured 22.15 million Btu of solar energy was delivered to system loads during the reporting period, a total of 0.03 million Btu (9 kWh) of operating energy was required for each one million Btu of solar energy delivered to the system loads.

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, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy.

The Solaron Duffield Solar Energy System has a heat pump for auxiliary space heating purposes. However, the heat pump is not used as a stand-alone unit, but rather in conjunction with an off-peak storage tank and associated hardware. As discussed in the Space Heating Subsystem section, the average COP for the overall heat pump system (not including the electrical strip heaters) was approximately 1.63 for the reporting period. Auxiliary energy for the heat strips and hot water heating is also provided by electricity and the COP for both the strips and hot water heating element is considered to be 1.0 for computational purposes.

Energy savings for the six month reporting period are presented in Table 5-1. During this time the system realized a gross electrical energy savings of 16.83 million Btu, which is the amount of solar energy supplied to the hot water subsystem and space heating subsystem (with appropriate COP adjustment). Since 0.13 million Btu were required to operate the hot water subsystem recirculation pump, the net savings for the hot water subsystem amounted to 1.80 million Btu. The net savings for the space heating subsystem, which is not charged with any operating energy deduction, totaled 14.90 million Btu. The ECSS blower consumed 0.55 million Btu of operating energy, so the net electrical energy savings for the entire solar energy system were 16.15 million Btu (4732 kWh), or approximately 3 barrels of oil.

TABLE 5-1
ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)		ECSS Operating Energy (Million Btu)	Net Electrical Energy Savings (Million Btu)		Fossil Equivalent At Source (Million Btu)
	Hot Water	Space Heating		(Million Btu)	(kWh)	
Oct 79	0.192	1.414	0.080	1.526	447	5.087
Nov 79	0.258	4.082	0.104	4.236	1,241	14.120
Dec 79	0.320	2.752	0.120	2.952	865	9.840
Jan 80	0.183	0.691	0.040	0.834	244	2.780
Feb 80	0.413	3.388	0.112	3.689	1,081	12.297
Mar 80	0.432	2.575	0.096	2.911	853	9.703
Total	1.798	14.902	0.552	16.148	4,731	53.827
Average	0.300	2.484	0.092	2.69	789	8.971

It should be noted that all values relating to space heating savings are based only on the measured solar energy contribution to the space heating load. There are some transport and storage losses present in this solar energy system, but they were not considered in any savings computations.

6.0 MAINTENANCE

This section provides a summary of all known maintenance visits made to the Solaron Duffield site from the time it went on line until the closing of the data assessment period.

December 5, 1979

- Fixed all control problems and replaced stripped gear on damper.

January 16, 1980

- Sealed all duct leaks.

7. SUMMARY AND CONCLUSIONS

The following paragraphs provide a brief summary of all pertinent parameters for the Solaron Duffield Solar Energy System for the period from October 1979 to March 1980. A more detailed discussion can be found in the applicable preceding sections.

During the reporting period, the measured daily average incident insolation in the plane of the collector array was 793 Btu/Ft^2 . This was 34 percent below the long-term daily average of $1,207 \text{ Btu/Ft}^2$. During the same period the measured average outdoor ambient temperature was 41°F . This was five degrees below the long-term average of 46°F . As a result 4,392 heating degree-days were accumulated, as compared to the long-term average of 3,492 heating degree-days.

The solar energy system satisfied 39 percent of the total measured load (hot water plus space heating) during the six month reporting period. This did not agree with the expected value of 24 percent for the reporting period. The exact cause for the variation is suspected to be due to computational variations between measured conditions and the f-Chart assumptions used in deriving the expected value.

A total of 62.03 million Btu of incident solar energy was measured in the plane of the collector array during the reporting period. The system collected 23.45 million Btu of the available energy, which represents a collector array efficiency of 38 percent. During the periods when the collector array was active, a total of 42.70 million Btu was measured in the plane of the collector array. Therefore, the operational collector efficiency was 55 percent.

During the reporting period a total of 16.56 million Btu of solar energy was delivered to the storage bin. During this same time 16.43 million Btu were removed from storage for support of the space heating load. During this period the net change in stored energy was 0.05 million Btu and 0.08 million Btu were lost from storage. The average storage efficiency was 0.96 and the average temperature was 80°F .

The hot water load for the six month reporting period was 5.71 million Btu. A total of 1.93 million Btu of solar energy and 5.58 million Btu of auxiliary energy were applied to the hot water load, which represents a weighted hot water solar fraction of 28 percent. The average daily consumption of hot water was 56 gallons, delivered at an average temperature of 126°F. A total of 2.77 million Btu was lost from the hot water tank, the preheat tank, and the subsystem piping during the reporting period.

The measured space heating load was 51.91 million Btu for the reporting period, and the heating solar fraction was 39 percent. During the heating season a total of 20.22 million Btu of measured solar energy and 31.69 million Btu of auxiliary thermal energy were actually delivered to the space heating load, and this energy maintained an average building temperature of 73°F. However, a total of 47.35 million Btu of auxiliary thermal energy was actually added to the space heating subsystem by the compressor and heat strips during the primary heating season when the system was operating in a defined heating mode.

A total of 0.68 million Btu, or 199 kWh, of electrical operating energy was required to support the solar energy system during the six month reporting period. This does not include the electrical energy required to operate the fan, pump or heat pump in the auxiliary system. These would be required for operation of the space heating subsystem regardless of the presence of the solar energy system.

Gross electrical energy savings for the six month reporting period were 16.83 million Btu. However, when the 0.68 million Btu of electrical operating energy is taken into account, the net electrical energy savings were 16.15 million Btu, or 4,732 kWh, or approximately 3 barrels of oil. If a 30 percent efficiency is assumed for power generation and distribution, then the net electrical energy savings translate into a savings of 53.83 million Btu in generating station fuel requirements or approximately 9 barrels of oil. It should also be noted that the electrical energy savings are based only on the measured amount of solar energy delivered to the space heating subsystem.

8. REFERENCES

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APPENDIX A
DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

APPENDIX A
DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

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 frame-work 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.

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 incident solar energy 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 incident energy 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 collector array efficiency reported here.

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 electrical or fossil fuel, solar energy, and the operating energy for the subsystem. In addition, the solar fraction for the subsystem 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 affect directly 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 (HWAEE) 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.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.
- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.
- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.
- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.
- AUXILIARY THERMAL USED (HAT) 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 ELECTRIC FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.
- ELECTRICAL ENERGY SAVINGS (HSVE) 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.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.
- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

ENVIRONMENTAL SUMMARY

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

- TOTAL INSOLATION (SE) is accumulated total incident solar energy upon the gross collector array measured at the site.
- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.
- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.
- WIND SPEED (WIND) is the average wind speed measured 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 FOR
SOLARON DUFFIELD

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR SOLARON DUFFIELD

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. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60) \sum [I_{001} \times \text{AREA}] \times \Delta\tau$$

where I_{001} is the solar radiation measurement provided by the pyranometer in $\text{Btu/ft}^2\text{-hr}$, 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

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

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 $\text{Btu}/(\text{lb}_m \cdot ^\circ\text{F})$, of the heat transfer fluid and ΔT , in $^\circ\text{F}$, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{\text{out}}) - H_a(T_{\text{in}})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m , of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

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

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 Solaron Duffield 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 ASSESSMENT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

AVERAGE BUILDING TEMPERATURE (°F)

$$TB = (1/60) \times \Sigma T601 \times \Delta\tau$$

AVERAGE AMBIENT TEMPERATURE (°F)

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

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

FOR ± 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT²)

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

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

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

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

$$HRF = 0.24 + 0.444 \times HR$$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO
OF THE TRANSPORT AIR. THIS FUNCTION IS USED WHENEVER THE
HUMIDITY RATIO WILL REMAIN CONSTANT AS THE TRANSPORT AIR FLOWS
THROUGH A HEAT EXCHANGING DEVICE

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$$SECA = \Sigma [(M101 \times (T150 - T100) + (M100 - M101) \times (T150 - T001)) \times HRF] \times \Delta\tau$$

NOTE THAT THIS EQUATION ACCOUNTS FOR LEAKAGE FLOW FROM THE OUTSIDE
ENVIRONMENT INTO THE COLLECTOR ARRAY.

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TST = (1/60) \times \Sigma [(T200 + T201 + T202)/3] \times \Delta\tau$$

SOLAR ENERGY TO STORAGE (BTU)

$$STEI = \Sigma [0.5 \times (M200 + M202) \times HRF \times (T102 - T152)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE (BTU)

$$STEO = \Sigma [0.5 \times (M200 + M202) \times HRF \times (T102 - T152)] \times \Delta\tau$$

SOLAR ENERGY DELIVERED TO LOAD FROM STORAGE (BTU)

$$HSES = M600 \times HRF \times (T450 - T601) \text{ WHEN HEATING FROM STORAGE}$$

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD(T_2, T_1) = \int_{T_1}^{T_2} C_p(T) dT$$

THIS FUNCTION COMPUTES THE ENTHALPY CHANGE OF WATER AS IT PASSES THROUGH A HEAT EXCHANGING DEVICE.

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

$$HWSE = \Sigma [M301 \times HWD(T351, T301)] \times \Delta\tau$$

SOLAR ENERGY DELIVERED TO LOAD FROM COLLECTOR ARRAY (BTU)

$$CSEOH1 = M600 \times HRF \times (T450 - T601)$$

ECSS OPERATING ENERGY (BTU)

$$CSOPE = 56.8833 \times \Sigma EP100 \times \Delta\tau$$

HOT WATER LOAD (BTU)

$$HWL = \Sigma [M302 \times HWD(T352, T302)] \times \Delta\tau$$

HOT WATER CONSUMED (GALLONS)

$$HWCSM = \Sigma WD302 \times \Delta\tau$$

SOLAR ENERGY TO HOT WATER LOAD (BTU)

$$HWSE1 = \Sigma [M302 \times HWD(T303, T302)] \times \Delta\tau$$

HOT WATER SUBSYSTEM OPERATING ENERGY (BTU)

$$\text{HWOPE} = 56.8833 \times \Sigma \text{EP301} \times \Delta\tau$$

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

$$\text{HWAEE} = 56.8833 \times \Sigma \text{EP302} \times \Delta\tau$$

HEAT PUMP SYSTEM POWER (BTU)

$$\text{HPPWR} = 56.8833 \times \Sigma [\text{EP402} + \text{EP404}] \times \Delta\tau$$

WHEN HEAT PUMP IS IN A HEATING MODE

ENERGY DELIVERED BY HEAT PUMP SYSTEM (BTU)

$$\text{HTHPDIR} = \Sigma [\text{M201} \times \text{HWD} (\text{T401}, \text{T451})] \times \Delta\tau$$

WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$\text{HTHPSTO} = \Sigma [\text{M201} \times \text{HWD} (\text{T401}, \text{T451})] \times \Delta\tau$$

WHEN HEATING FROM OFF PEAK STORAGE TANK

AUXILIARY THERMAL ENERGY FROM HEAT PUMP (BTU)

$$\text{HAT2} = \Sigma [\text{M201} \times \text{HWD} (\text{T207}, \text{T257})] \times \Delta\tau$$

WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$\text{HAT3} = \Sigma [\text{M201} \times \text{HWD} (\text{T207}, \text{T257})] \times \Delta\tau$$

WHEN CHARGING OFF PEAK STORAGE WITH HEAT PUMP

AUXILIARY ELECTRICAL FUEL ENERGY TO HEAT PUMP COMPRESSOR (BTU)

$$\text{HAE1} = 56.8833 \times \Sigma [\text{EP402}-\text{EP403}] \times \Delta\tau$$

WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$\text{HAE2} = 56.8833 \times \Sigma [\text{EP402}-\text{EP403}] \times \Delta\tau$$

WHEN CHARGING OFF PEAK STORAGE WITH HEAT PUMP

AUXILIARY ELECTRICAL FUEL ENERGY TO HEAT STRIPS (BTU)

$$\text{HAE3} = 56.8833 \times \Sigma \text{EP401} \times \Delta\tau$$

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$$SEA = CLAREA \times SE$$

COLLECTED SOLAR ENERGY (BTU/FT²)

$$SEC = SECA/CLAREA$$

COLLECTOR ARRAY EFFICIENCY

$$CAREF = SECA/SEA$$

CHANGE IN STORED ENERGY (BTU)

$$STECH = STECH1 - STECH1_p$$

WHERE THE SUBSCRIPT _p REFERS TO A PRIOR REFERENCE VALUE

STORAGE EFFICIENCY

$$STEFF = (STECH + STEO)/STE1$$

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

$$CSEO = STEO + CSEOH1 + HWSE$$

ECSS SOLAR CONVERSION EFFICIENCY

$$CSCEF = CSEO/SEA$$

SUPPLY WATER TEMPERATURE (°F)

$$TSW = T302$$

HOT WATER TEMPERATURE (°F)

$$THW = T352$$

BOTH TSW AND THW ARE COMPUTED ONLY WHEN FLOW EXISTS IN THE
SUBSYSTEM, OTHERWISE THEY ARE SET EQUAL TO THE VALUES OBTAINED
DURING THE PREVIOUS FLOW PERIOD.

AUXILIARY THERMAL ENERGY TO HOT WATER SUBSYSTEM (BTU)

$$HWAT = HWAE$$

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

$$HWSVE = HWSE1 - HWOPE$$

HOT WATER SOLAR FRACTION (PERCENT)

$$HWSFR = 100 \times HWTKE/(HWTKE + HWTKAUX)$$

WHERE HWTKE AND HWTKAUX REPRESENT THE CURRENT SOLAR AND
AUXILIARY ENERGY CONTENT OF THE HOT WATER TANK

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HSE = HSES + CSE01$$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$$HOPE = 56.8833 \times \Sigma [EP400 + EP403 + EP404] \times \Delta\tau$$

WHENEVER SYSTEM OPERATING IN A HEATING MODE

AUXILIARY ELECTRICAL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HAE = HAE1 + HAE2 + HAE3$$

TOTAL ENERGY DELIVERED BY HEAT PUMP SYSTEM (BTU)

$$HLHP = HTHPSTO + HTHPDIR$$

SPACE HEATING LOAD (BTU)

$$HL = HAE3 + HSE + HLHP$$

AUXILIARY THERMAL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HAT = HAE3 + HAT2 + HAT3$$

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

$$HSFR = 100 \times HSE/HL$$

SPECIAL HEAT PUMP TERMS

NORMALIZED CAPACITY

$$CAPN = 0.325 + TA \times (0.0162 - 0.00005 \times TA)$$

HEAT PUMP FRACTION

$$HPF = 1$$

$$TA > 40$$

$$HPF = 1.11 \times CAPN \times (TB - 40)/(TB - TA)$$

$$2 \leq TA \leq 40$$

$$HPF = 0$$

$$TA < 2$$

HEAT PUMP OVERALL SYSTEM COP

$$HCOP = HLHP/HPPWR$$

WHERE HCOP IS BASED ON A TOTAL OF SIX

MONTHS OF SYSTEM OPERATION

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

$$\text{HSVE} = \text{HSE} \times (\text{HPF}/\text{HCOP} + 1 - \text{HCOP})$$

IF $\text{TA} \geq 2$

$$\text{HSVE} = 0.5 \times \text{HSE} \times (1 + \text{HCOP})/\text{HCOP}$$

IF $\text{TA} < 2$

SYSTEM LOAD (BTU)

$$\text{SYSL} = \text{HL} + \text{HWL}$$

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

$$\text{SFR} = (\text{HL} \times \text{HSFR} + \text{HWL} \times \text{HWSFR})/\text{SYSL}$$

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

$$\text{SEL} = \text{HWSE} + \text{HSE}$$

SYSTEM OPERATING ENERGY (BTU)

$$\text{SYSOPE} = \text{HWOPE} + \text{HOPE} + \text{CSOPE}$$

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

$$\text{AXT} = \text{HWAT} + \text{HAT}$$

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

$$\text{AXE} = \text{HWAE} + \text{HAE}$$

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

$$\text{TSVE} = \text{HWSVE} + \text{HSVE} - \text{CSOPE}$$

TOTAL ENERGY CONSUMED (BTU)

$$\text{TECSM} = \text{SYSOPE} + \text{AXE} + \text{SECA}$$

SYSTEM PERFORMANCE FACTOR

$$\text{SYSPF} = \text{SYFL}/(\text{AXE} + \text{SYSOPE}) \times 3.33$$

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: SOLARON DUFF. 116. LOCATION: DUFFIELD VA
 ANALYST: L. MARTIN FORIVE NO.: 77.
 COLLECTOR TILT: 40.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)
 LATITUDE: 36.50 (DEGREES) RUN DATE: 08/30/79

MONTH	HRRAR	HBAR	KRRAR	PRAR	SBAR	HDD	CDD	TBAR
JAN	1514.	645.	0.42629	1.568	1012.	800	0	39.
FEB	1963.	885.	0.45097	1.368	1210.	472	5	41.
MAR	2528.	1217.	0.48171	1.168	1421.	527	11	48.
APR	3096.	1589.	0.51321	0.903	1578.	210	25	59.
MAY	3491.	1781.	0.51161	0.880	1567.	65	129	67.
JUN	3631.	1891.	0.52091	0.834	1577.	0	278	74.
JUL	3549.	1799.	0.50664	0.855	1538.	0	377	77.
AUG	3239.	1641.	0.50662	0.941	1544.	0	347	76.
SEP	2729.	1363.	0.50110	1.096	1499.	17	179	70.
OCT	2125.	1099.	0.51706	1.330	1461.	195	36	60.
NOV	1617.	763.	0.47207	1.551	1184.	499	0	48.
DEC	1388.	583.	0.41956	1.635	952.	777	0	40.

LEGEND:

HGBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.
 HRRAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.
 KRRAR ==> RATIO OF HRRAR TO HGBAR.
 PRAR ==> 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.F., 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.