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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR FERN, TUNKHANNOCK, PENNSYLVANIA

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For the U. S. Department of Energy

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Solar Energy

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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. Other documents specifically related to this system are References [1] and [2].*

*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The Fern* Tunkhannock solar energy system was designed to provide both space heating and domestic hot water preheating for a 1,000 square foot single-family residence in Tunkhannock, Pennsylvania. Solar energy collection is accomplished with flat-plate collectors using air as the transport fluid. The collector array has a gross area of 208.5 square feet and faces 15 degrees west of south at an angle of 45 degrees from the horizontal. Energy is transferred to and from storage by means of a liquid-to-air heat exchanger. Storage capacity is 240 gallons of water in the main tanks (two tanks of 120 gallons each) and 40 gallons in the domestic hot water tank. Auxiliary energy for the hot water subsystem is provided by electricity, and for the space heating subsystem by fuel oil. The hot water heater is rated at 4kw, and the space heating furnace at 100,000 Btu/hr. The system, shown schematically in Figure 2-1, has five modes of operation. The sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 [3]. The measurement symbol prefixes: W, T, EP, I and F represent respectively: flow rate, temperature, electric power, insolation, and fossil fuel consumption.

Mode 1 - Collector-to-Space Heating: In this mode, solar heated air is delivered directly from the collector array to the conditioned space. This mode is entered whenever there is a demand for space heating and the collector array temperature exceeds 95°F.

Mode 2 - Storage-to-Space Heating: This mode is entered whenever a demand for space heating exists, there is insufficient solar radiation available to directly satisfy this demand, and if the storage tank temperature is high enough (95°F) to supply useful energy. In this mode, heated water is taken from storage and circulated through the liquid side of the liquid-to-air heat exchanger located in the heating system supply duct. Air is then passed through the air side of the heat exchanger, where it is warmed for delivery to the house.

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*Solafern Ltd., formerly Fern, Inc. is the system contractor.

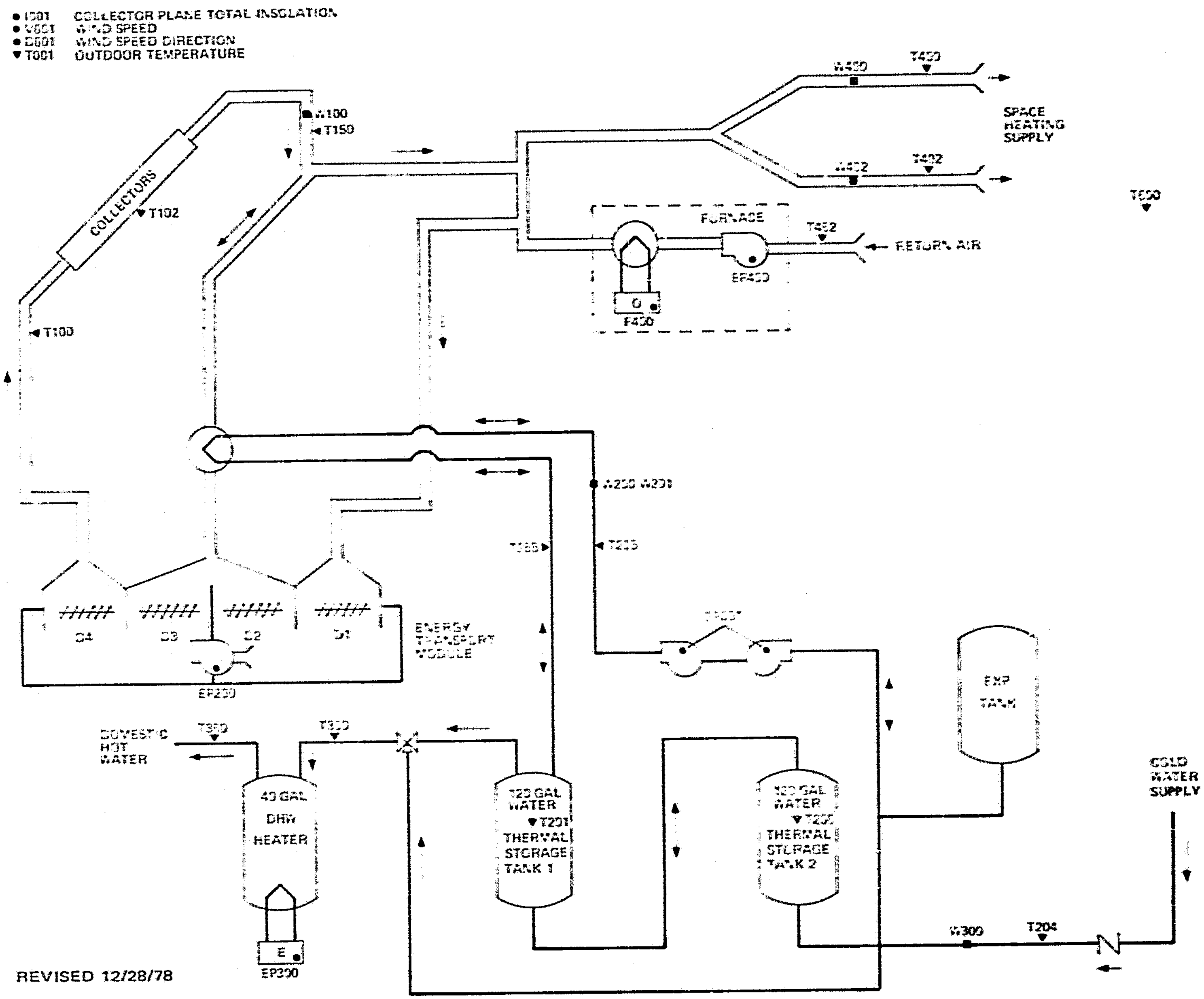


Figure 2-1 Fern Tunkhannock Solar Energy System Schematic

Mode 3 - Collector-to-Storage: The system operates in this mode whenever the space heating demands have been satisfied and additional solar energy is available for heating storage. A differential of 20°F between collector and storage is required before collected energy can be delivered to storage. Solar heated air is passed through the heat exchanger where it warms water that is being circulated from the storage tanks.

Mode 4 - Domestic Hot Water Preheating: This mode exists whenever there is a demand for hot water. Makeup water is delivered to storage where it is preheated before going to the hot water heater.

Mode 5 - Collector-to-Storage and Auxiliary Space Heating: This mode is entered whenever the room thermostat is raised 3°F or more above the solar energy system activation temperature, or if the room temperature drops 3°F below the solar energy system activation temperature. Under these circumstances, auxiliary energy is used to heat the house and any available solar energy is delivered to storage. When the house temperature recovers, the system will switch back to the direct Collector-to-Space Heating mode.

2.1 Typical System Operation

Curves depicting typical system operation on a cool bright day (March 28, 1979) 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). On this particular day the array cycled on momentarily at 0908 hours and then started normal operation 0924 hours. The array continued to operate until 1610 hours and then shut down for the day.

Figure 2.1-1 (b) shows typical collector array temperatures during the day. During the early morning hours the collector array outlet temperature (T150) was being influenced by warm air leakage from the auxiliary furnace. At the same time, the collector array inlet temperature (T100) and the collector absorber plate temperature (T102) were in a comparatively quiescent state. As the sun started to rise at approximately 0700 hours T102 began to rise rapidly and reached 181°F before the system began normal operation at 0924 hours. It should be noted that T102 is not the control sensor that governs system operation. The actual system controls are set up such that a collector temperature (not necessarily the absorber plate temperature) of 95°F is required to initiate the direct heating mode (collector-to-space heating), and a differential temperature of 20°F between the collector and storage is required before collected energy can be delivered to storage. These operating temperature constraints are mentioned to make the reader aware that monitoring instrumentation and control sensors have no direct correlation, but monitoring instrumentation can provide sufficient gross data to determine if each operational mode is functioning within a reasonable range of control temperature sensor limits.

During the operational period T102 generally tracked the insolation level and T150 showed some lag, as would be expected. The behavior of T100 was influenced by the mode of operation that the system was in. On this particular day, the system switched back and forth several times between direct space heating from the collector array and storing of collected solar energy. During periods of direct space heating T100 was primarily being influenced by the temperature of return air from the interior of the house. When collected energy was being stored, T100 was primarily governed by the collector array outlet temperature and the amount of energy removed from the air stream by the storage loop heat exchanger.

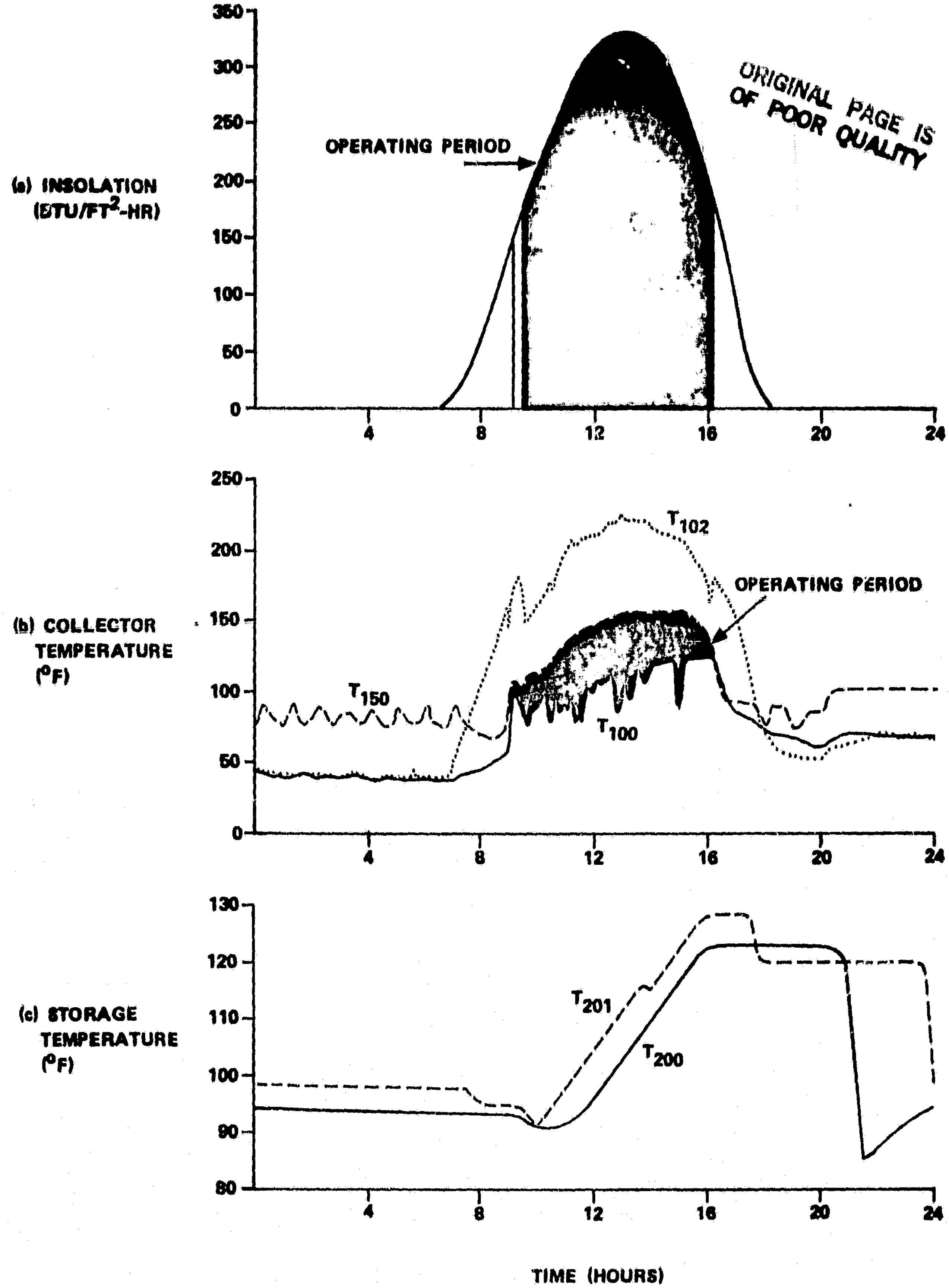


Figure 2.1-1 Typical System Operating Parameters

Figure 2.1-1 (c) shows the temperature profile of the two storage tanks in the system (each 120 gallon tank has only one sensor). During the early morning hours all space heating demands were satisfied with the auxiliary furnace and the storage tanks remained relatively stable. Although the average temperature for the two tanks was slightly above 95°F (the minimum storage tank temperature required for heating from storage) it must again be emphasized that the monitoring instrumentation does not necessarily correlate with system control instrumentation. At 0730 hours approximately 17 gallons of hot water was used and a temperature change occurred in storage tank number one. After the collector array began operating at 0924 hours, both tanks began to warm up and continued to do so until the collector array turned off at 1610 hours. At 1730 hours another large hot water draw (29 gallons) occurred and then at 2010 the system began to use stored solar energy for space heating. For the remainder of the day, stored solar energy was able to satisfy the space heating demand and the auxiliary system remained off.

It is difficult to draw any concrete conclusions about the storage subsystem behavior based on the temperature profiles presented in Figure 2.1-1 (c). As noted previously, each 120 gallon tank has only one temperature sensor. Also, the typical storage loop flowrate is fairly low (approximately two gallons per minute) and makeup water feeds directly into tank number two whenever hot water is used. These factors, coupled with any stratification that occurs in the tanks and actual sensor location, preclude any in-depth analysis.

2.2 System Operating Sequence

Figure 2.2-1 presents bar charts showing typical system operating sequences for March 28, 1979. This data correlates with the curves presented in Figure 2.1-1 and provides some additional insight into those curves.

There are two interesting observations to be made from Figure 2.2-1. First is the cyclic operation of the system as it switched between direct space heating from the collector array and storing of solar energy. The system cycled rapidly because the space heating demands were satisfied very quickly and the system would immediately begin to charge storage. If a slight delay were to be incorporated before allowing mode switching, the system might operate more efficiently because mode duration would be longer. The second observation relates to the use of hot water auxiliary energy. It will be noted that auxiliary energy was used almost every time hot water was drawn. This is because the hot water subsystem only uses storage to preheat makeup water when hot water is consumed. This type of design does not lend itself to supplying the vast majority of sporadic loads but does save the energy required to operate a circulation system.

If a circulation loop was added to the domestic hot water loop, the hot water tank would receive more support from the solar energy system. However, as previously noted, this would require the expenditure of additional operating energy. In addition the performance of the space heating subsystem would be reduced because there would be less stored energy available for support of space heating loads. Also, higher initial costs would be incurred for additional hardware. Consequently, no definite recommendations can be made in this area.

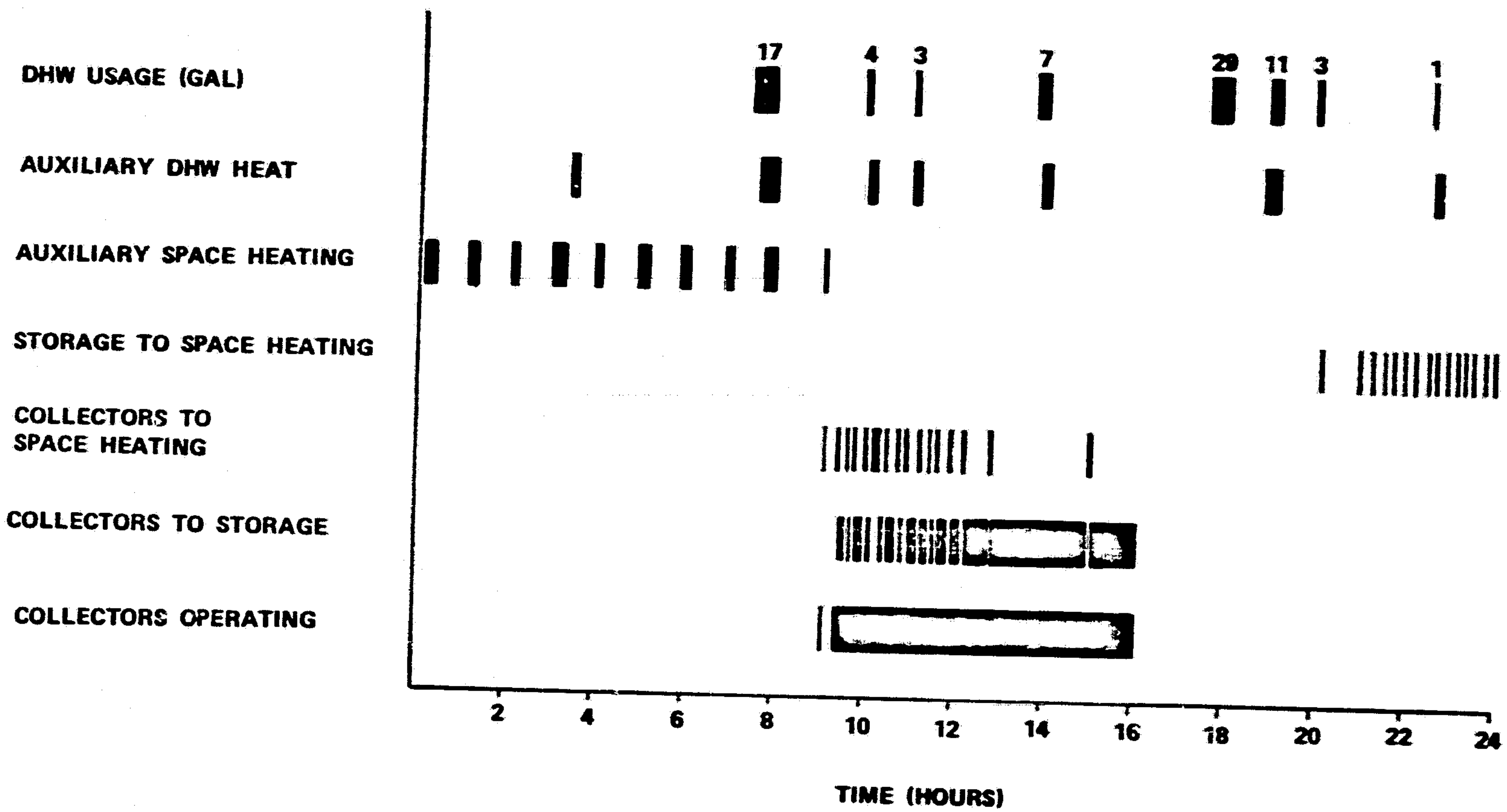


Figure 2.2-1 Typical System Operating Sequence

3. PERFORMANCE ASSESSMENT

The performance of the Fern Tunkhannock 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.

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 Fern Tunkhannock solar energy system was initially brought on line in March 1978. 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 system check-out phase, two sensors were found to be defective. The outside ambient temperature sensor (T001) and the temperature sensor on the cold side of storage (T205) were both generating erroneous data. A site visit was made in late July 1978 to repair the instrumentation and to make several other modifications and tests. This was done to bring the site up to the latest configuration and have it ready for operation at the start of the heating season.

In early October the site maintenance contractor visited the site to install an improved back draft damper in the duct between the collector outlet and existing furnace ductwork. However, some leaks were inadvertently introduced during this procedure and a second contractor visit was required in late November to repair the leaks. However, the measured collector array performance was reduced during October and November due to these leaks.

During a December site visit an interesting condition was noted relating to the available incident insolation on the collector array. The topography of the surrounding terrain is such that a mountain shades the collector array and pyranometer during the late afternoon hours. This condition caused some reduction in system performance during the heating season but had no effect once the sun angle increased to a point where the mountain did not block the sun's rays. This occurred approximately two to three months on either side of the winter solstice.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the Fern Tunkhannock Solar Energy System located in Tunkhannock, Pennsylvania. 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" [3]. 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) [4] 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:

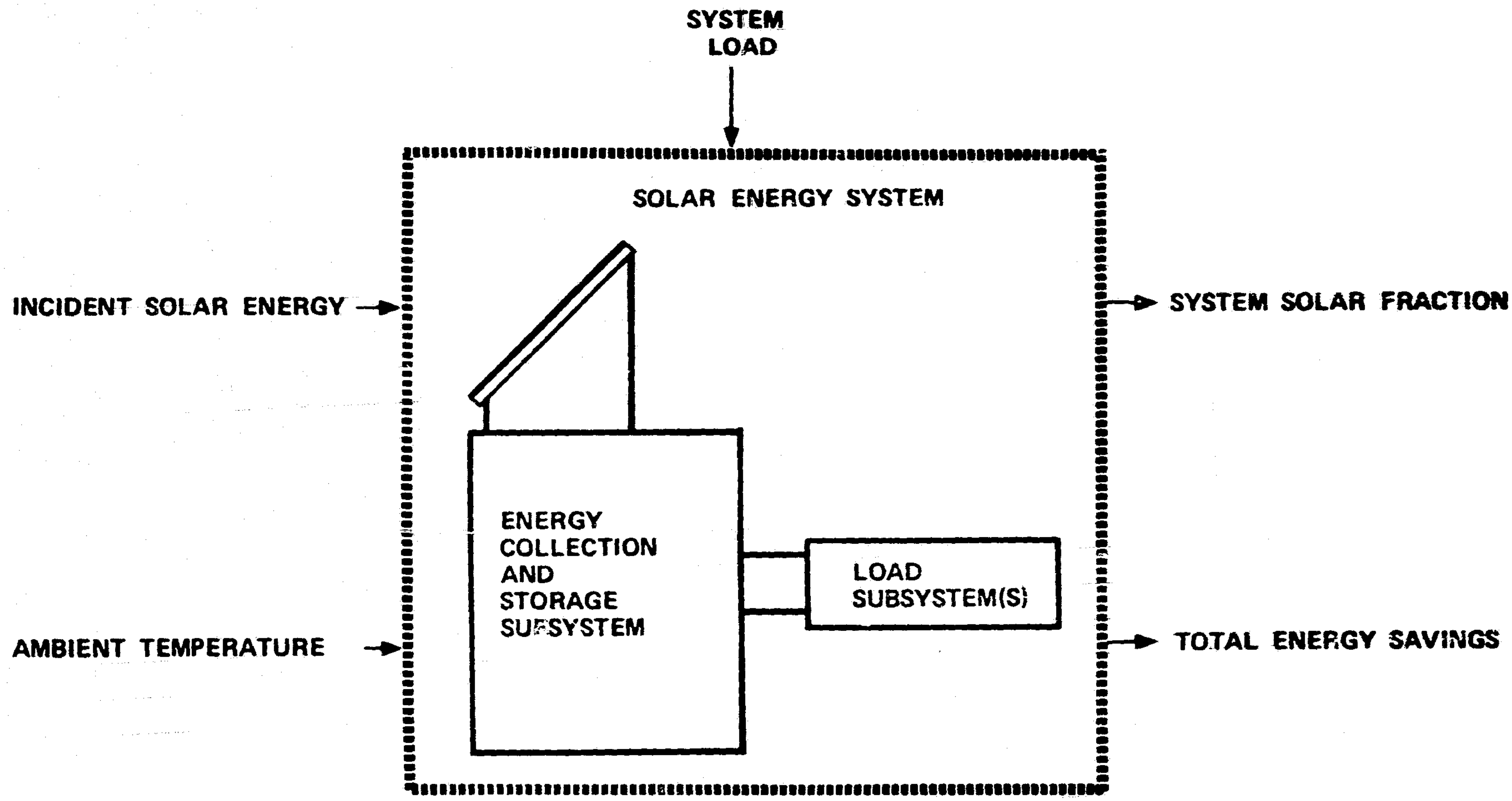


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

- Incident solar energy - The total solar energy incident on the collector array 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. 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 3.1-1

SYSTEM PERFORMANCE SUMMARY

FERN TUNKHANNOCK

Month	Daily Incident Solar Energy Per Unit Area (45° 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	
May 78	1,041	1,411	*	59	2.19	30	60	0.51
Jun 78	1,467	1,472	*	68	0.89	55	100	0.25
Jul 78	1,409	1,499	*	72	0.69	54	100	0.12
Aug 78	1,288	1,445	72	70	0.72	58	100	0.20
Sep 78	1,291	1,348	62	63	0.87	51	98	0.28
Oct 78	1,107	1,246	49	53	2.82	28	54	0.76
Nov 78	711	766	40	41	4.80	12	19	0.50
Dec 78	585	613	30	29	6.92	9	8	0.63
Jan 79	546	746	26	26	8.05	7	5	0.62
Feb 79	1,042	981	18	27	8.01	9	20	0.78
Mar 79	1,065	1,182	41	36	5.01	21	35	1.09
Apr 79	1,201	1,345	48	49	3.58	24	31	0.86
Total	--	--	--	--	44.55	--	--	6.61
Average	1,063	1,171	43	49 (44)**	3.71	17	31	0.55

* The outdoor ambient temperature sensor (T001) was defective during these months.

**Values in parentheses represent data for the Aug 78 through Apr 79 time period.

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 Fern Tunkhannock site for the 12 month report period, the long term average daily incident solar energy in the plane of the collector was 1,171 Btu/ft^2. The average daily measured value was 1,063 Btu/ft^2 which is about nine percent below the long term value. On a monthly basis, January of 1979 was the worst month with an average daily measured value of incident solar energy 27 percent below the long term average daily value. February 1978 was the best month with an average daily measured value six percent above the long term average daily value. On a long term basis it is obvious that the good and bad months almost 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 for the nine month period from August 1978 through April 1979 was 44°F at the Fern Tunkhannock site. This compares very favorably with the measured value of 43°F. A full year comparison cannot be given because the outdoor ambient temperature sensor was defective during the first three months of the report period.

It is interesting to note the strong influence that the local weather conditions had on the measured solar fraction. For example, the measured average outdoor ambient temperature in January 1979 was equal to the long term average, and in February 1979 it was nine degrees below the long term average. In January the measured insolation was 27 percent below the long term average and the measured solar fraction was seven percent. However, in February the measured insolation was six percent above the long term average and the measured solar fraction was nine percent. In March 1979 the measured insolation was ten percent below the long term average, but the measured average outdoor ambient temperature of 41°F was five degrees above the long term average and the measured solar fraction was 21 percent. This is exactly what would be expected because, even though the insolation was low, the measured average outdoor ambient temperature for March was 19°F above that noted for the January-February time period. These observations serve to reinforce the earlier statement concerning the impact of prevailing weather conditions on the performance of a solar energy system.

The system load has an important affect on the system solar fraction and the total energy savings. If the load is small and sufficient energy is available from the collectors, the system solar fraction can be expected to be large. However, the total energy savings will be less than under more nominal load conditions. This is illustrated by comparing the performance of the system during the summer (June, July and August) and winter (December, January and February) months. During the summer the space heating load was negligible and the system was used primarily to support the hot water load. As a result the system solar fraction was approximately six times higher than during the winter months. However, total savings during the winter were over three times greater than during the summer and the winter load was approximately an order of magnitude greater than the summer load.

Also presented in Table 3.1-1 are the measured and expected values of system solar fraction where system solar fraction is the ratio of solar energy applied to system loads to the total energy (solar plus auxiliary) applied to the loads. The expected values have been derived from a modified f-Chart analysis which uses measured weather and subsystem loads as inputs (f-Chart is the designation of a procedure that was developed by the Solar Energy Laboratory, University of Wisconsin, Madison, for modeling and designing solar energy systems [8]). The model used in the analysis is based on manufacturers' data and other known system parameters. The basis for the model 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 17 percent was considerably lower than the expected value of 31 percent generated by the modified f-Chart program. Although this variation is quite large, it must be realized that the f-Chart prediction model is not ideally suited to the type of system design used at Fern Tunkhannock. For example, the f-Chart model assumes either a recirculation loop or a perfectly insulated tank in the hot water subsystem. This is not the situation that exists in the site and is the reason that the expected solar fraction of 100 percent is computed during the summer (negligible heating load) months, as opposed to the measured values between 54 and 58 percent. However, even though the prediction model must use some assumptions that do not fit the solar energy system perfectly, the overall value of this analysis tool should not be underestimated. During the winter months, when the space heating load predominates, the predictions are generally more accurate. Significant variations during this time frame can generally be attributed to the various uncontrolled energy losses (leakage) that exist in the system.

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 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 computed energy savings for the Fern Tunkhannock solar energy system was 6.61 million Btu, or 1937 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 Fern Tunkhannock 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 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 Fern Tunkhannock 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 eacn month for the monthly performance assessment. This section presents the results of integrating the monthly data available on the four subsystems for the period May 1978 through April 1979.

3.2.1 Collector Array Subsystem

The Fern Tunkhannock collector array consists of six Solafern 3000 series flat-plate air collectors arranged in two parallel rows of three in-series collectors each. These collectors are a two-pass air heating type with a single glazing. Typical flowrate through each collector is approximately 275 Ft^3/Min. Details of the air flow path are shown in Figure 3.2.1-1 (a) and the collector array arrangement is shown schematically 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:

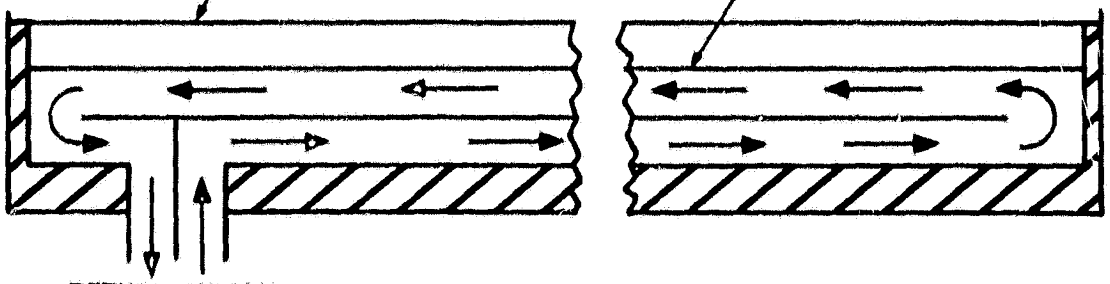
$$\eta_c = Q_s/Q_i \qquad (1)$$

where η_c = Collector array efficiency

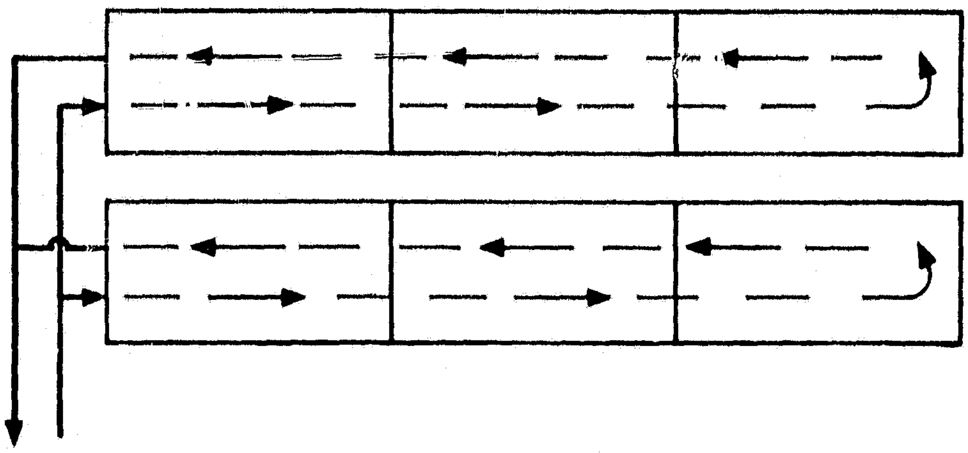
Q_s = Collected solar energy

Q_i = Incident solar energy

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



(a) Collector Air Flow Path



(b) Collector Array Arrangement

COLLECTOR ARRAY		SITE LOCATION	
TILT	– 45°	LATITUDE	– 41.55°N
AZIMUTH	– 15°W of S	LONGITUDE	– 77.95°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
May 78	6.73	1.70	0.25	4.87	0.35
Jun 78	9.18	2.34	0.26	7.00	0.33
Jul 78	9.11	2.28	0.25	6.81	0.33
Aug 78	8.33	2.15	0.26	6.34	0.34
Sep 78	8.08	2.01	0.25	6.23	0.32
Oct 78	7.16	1.78	0.25	5.76	0.31
Nov 78	4.45	0.98	0.22	3.52	0.28
Dec 78	3.78	0.87	0.23	2.40	0.36
Jan 79	3.53	0.74	0.21	2.10	0.35
Feb 79	6.08	1.29	0.21	3.82	0.34
Mar 79	6.88	1.83	0.27	4.82	0.38
Apr 79	7.51	1.91	0.25	5.06	0.38
Total	80.82	19.88	--	58.73	--
Average	6.74	1.66	0.25	4.89	0.34

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:

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

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 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.).

- 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 Fern Tunkhannock includes the months from December 1978 through April 1979. Although the system was operating prior to December 1978, there were some leakage problems in the system (primarily ductwork) that caused difficulties in the collector analysis. Therefore, months prior to December 1978 were not included in the data base.

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:

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

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:

*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 is assumed to be unity for 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

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

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:

$$b = F_R(\tau\alpha) \quad \text{and} \quad m = F_R U_L \qquad (6)$$

where the terms are as previously defined

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

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

The long term first order curve shown in Figure 3.2.1-2 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. The laboratory predicted instantaneous efficiency is not in close agreement with the curve derived from actual field operation. This

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

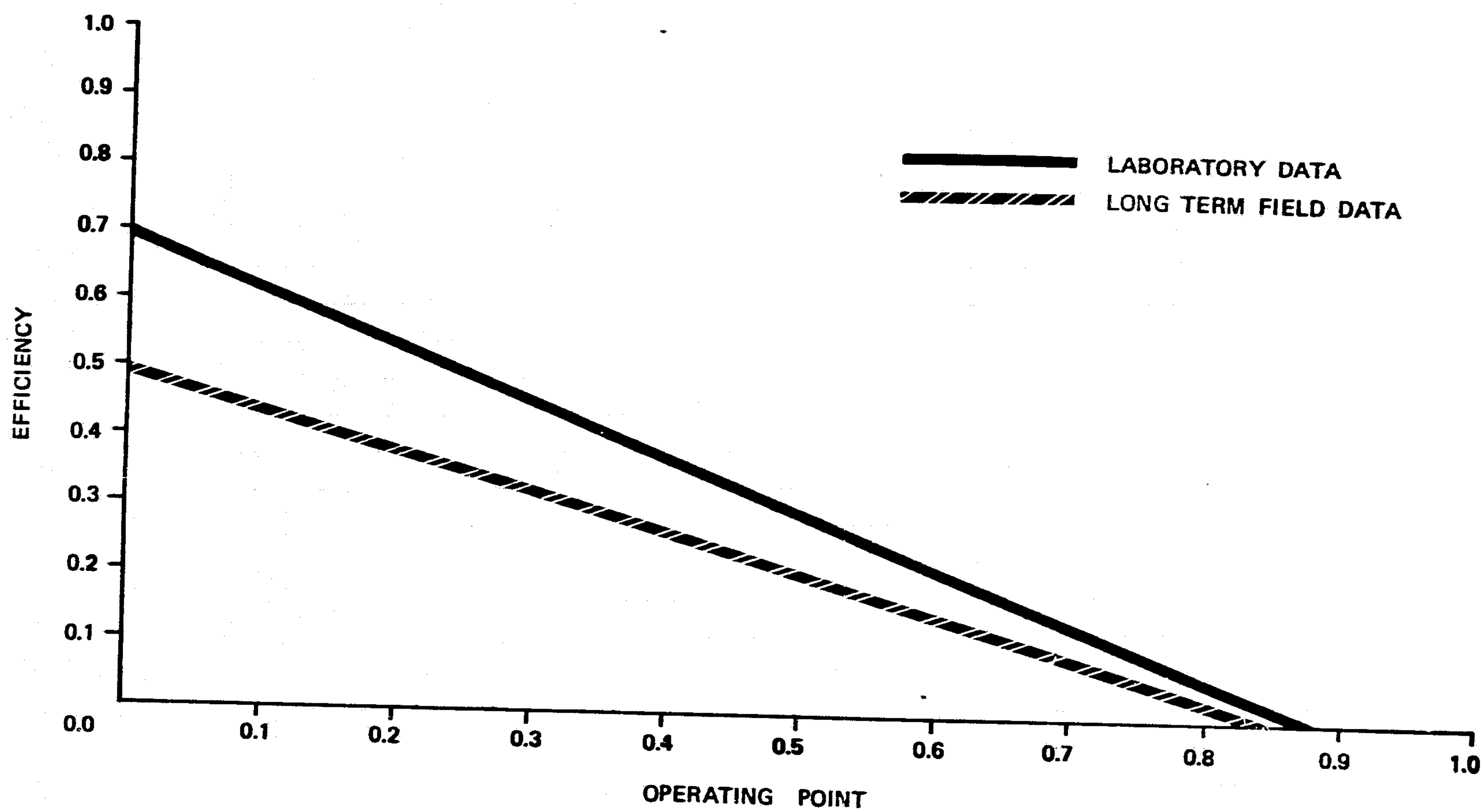


Figure 3.2.1-2 Fern Tunkhannock Collector Efficiency Curves

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.

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

Single panel laboratory data

$F_R(\tau\alpha) = 0.700$ $\quad$ $F_R U_L = -0.800$

Long term field data

$F_R(\tau\alpha) = 0.494$ $\quad$ $F_R U_L = -0.588$

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

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: FERN TUNKHANNOCK

TUNKHANNOCK, PENNSYLVANIA

Month	Collected Solar Energy (Million Btu)	Error	
		Field Derived Long Term	Laboratory Single Panel
Dec 78	0.776	0.002	-0.295
Jan 79	0.713	-0.016	-0.305
Feb 79	1.289	-0.062	-0.340
Mar 79	1.825	0.016	-0.288
Apr 79	1.912	0.003	-0.302
Average	1.303	-0.009	-0.305

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

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

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

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.

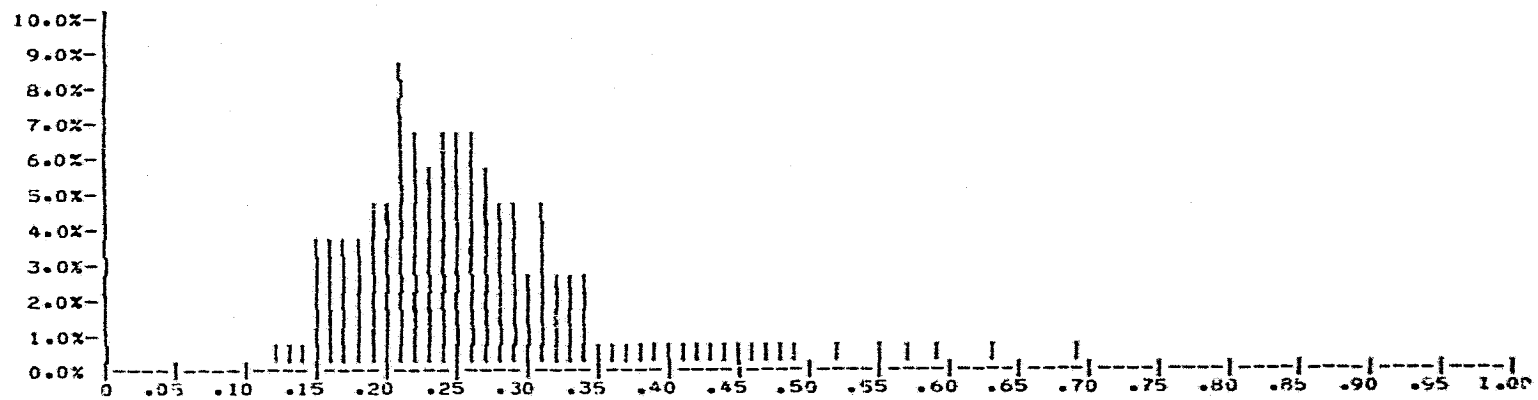
The values of "Collected Solar Energy" given in Table 3.2.1-2 are not necessarily identical with the values of "Collected Solar Energy" given in Table 3.2.1-1. Any variations are due to the differences in data processing between the software programs used to generate the monthly performance assessment 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 Fern Tunkhannock 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 -0.9 percent. For the curve derived from the laboratory single panel data, the error was -30.5 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 and the climatic factors of the site, i.e., incident solar energy and ambient temperature. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (February) and a typical summer month (August) operation. The approximate average operating point for February is at 0.25 and for August at 0.17. From Equation (3), when the temperature difference becomes larger between T_i and 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. Normally, 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. However, in this case, the operational collector efficiencies were almost identical for August and February, although August was slightly

OPERATING POINT HISTOGRAM – AUGUST



OPERATING POINT HISTOGRAM – FEBRUARY

ABCISSA = (Inlet Temperature–Ambient Temperature)/Insolation Deg F–Hr–SqFt/Btu

ORDINATE = Percent of Total Occurrences

Figure 3.2.1-3 Fern Tunkhannock Operating Point Histograms for Typical Winter and Summer Months higher. Again, the problem is suspected to be caused by duct leakages that may have resulted in measured collector array flow being less than the actual flow through the collector array. 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). On the average the operational collector array efficiency exceeded the collector array efficiency, which included the effect of the control system, by 38 percent.

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

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

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. Temperature sensor T205 was defective during May, June and July, so it was not possible to compute energy to or from storage and storage efficiency during those months. However, the remaining nine months provide a reasonable representation of overall storage performance.

During the nine month period of full data a total of 7.09 million Btu was delivered to the storage tanks and a total of 6.00 million Btu was removed for support of system loads. The net change in stored energy during this same time period was 0.13 million Btu, which leads to a storage efficiency of 0.86 and a total energy loss from storage of 0.96 million Btu for these nine months.

The computed storage efficiency of 0.86 is relatively high as compared to most solar energy systems. However, the average storage temperature during the period that efficiency was computed was only 90°F, so the high value of efficiency is not unrealistic. This is true because the potential for heat transfer becomes smaller as the differential temperature between the internal fluid and the external environment becomes smaller. However, this is not meant to detract in any way from the fact that the storage subsystem performed well during the reporting period. The system is well insulated and the effective heat transfer coefficient averaged only 6.6 Btu/Hr-°F during the nine month period.

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	*	*	0.01	*	93
Jun 78	*	*	0.02	*	111
Jul 78	*	*	-0.07	*	115
Aug 78	0.59	0.54	0.01	0.92	114
Sep 78	0.62	0.55	0.02	0.92	107
Oct 78	1.03	0.79	0.03	0.80	95
Nov 78	0.57	0.55	-0.02	0.94	83
Dec 78	0.57	0.55	-0.03	0.92	78
Jan 79	0.48	0.52	-0.04	1.00	70
Feb 79	0.73	0.57	0.11	0.93	77
Mar 79	1.24	1.06	-0.05	0.82	88
Apr 79	1.26	0.87	0.10	0.77	94
Total	7.09	6.00	0.09 (0.13)**	--	--
Average	0.79	0.67	0.01 (0.91)	0.86	94 (90)

* Temperature sensor T205 (reference Figure 2-1) was defective during these months.
** Values in parentheses represent data for the Aug 78 through Apr 79 time period.

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 Fern Tunkhannock 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 energy supplied shown in the Table.

For the 12 month period from May 1978 through April 1979, the solar energy system supplied a total of 5.85 million Btu to the hot water load. The total hot water load for this period was 12.15 million Btu, and the weighted average monthly solar fraction was 44 percent.

The monthly average hot water load during the reporting period was 1.01 million Btu. This is based on an average daily consumption of 53 gallons, delivered at an average temperature of 137°F and supplied to the system at an average temperature of 63°F. The temperature of the supply water ranged from a low of 54°F in January, February, and March to a high of 74°F in August.

Each month an average of 0.49 million Btu of solar energy and 0.73 million Btu of auxiliary thermal (electrical) energy were supplied to the hot water subsystem. Since the average monthly hot water load was 1.01 million Btu, an average of 0.21 million Btu was lost from the hot water tank each month.

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)					
			Supply	Delivery	Solar	Auxiliary Thermal	Auxiliary	
May 78	1.21	1,890	62	135	0.54	0.85	0.85	43
Jun 78	0.81	1,431	67	134	0.46	0.48	0.48	53
Jul 78	0.67	1,278	72	133	0.40	0.46	0.46	53
Aug 78	0.72	1,424	74	132	0.49	0.43	0.43	58
Sep 78	0.83	1,558	71	133	0.47	0.59	0.59	49
Oct 78	0.95	1,721	67	138	0.47	0.87	0.87	45
Nov 78	0.96	1,583	62	142	0.38	0.71	0.71	39
Dec 79	1.02	1,427	59	146	0.39	0.77	0.77	37
Jan 79	1.28	1,845	54	142	0.46	1.02	1.02	34
Feb 79	1.12	1,509	54	141	0.48	0.82	0.82	39
Mar 79	1.44	1,864	54	136	0.72	0.96	0.96	45
Apr 79	1.14	1,599	58	134	0.59	0.76	0.76	46
Total	12.15	19,129	--	--	5.85	8.72	8.72	--
Average	1.01	1,594	63	137	0.49	0.73	0.73	44

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 Fern Tunkhannock space heating subsystem is presented in Table 3.2.4-1. For the 12 month period from May 1978 through April 1979, the solar energy system supplied a total of 2.16 million Btu to the space heating load. The total heating load for this period was 32.40 million Btu, and the average monthly solar fraction was seven percent.

The measured space heating subsystem performance was lower than expected during the reporting period. If the assumption is made that the hot water solar fraction of 44 percent was approximately equal to the design value, then a space heating solar fraction of 37 percent would have been necessary for the system to achieve the design goal of 39 percent for the overall system solar fraction.

It must be emphasized that all values presented in this section relating to the performance of the space heating subsystem are based on measured parameters. In other words the space heating load, solar contribution and auxiliary thermal energy used are all determined based on the measured output of the space heating subsystem. These measured values do not include any of the various solar energy losses that are present in the system. However, solar energy losses are generally added to the interior of the house and, as such, represent an uncontrolled (unmeasured) contribution to the space heating load. At the Fern Tunkhannock site these solar energy losses occur during energy transport between the various

TABLE 3.2.4-1

HEATING SUBSYSTEM PERFORMANCE

Month	Heating Parameters			Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
	Load (Million Btu)	Temperatures (°F)			Auxiliary		
		Building	Outdoor	Solar	Auxiliary Thermal	Auxiliary	
May 78	0.98	73	*	0.14	0.84	1.40	15
Jun 78	0.08	74	*	0.06	0.02	0.03	74
Jul 78	0.02	78	*	0.02	0.0	0.0	100
Aug 78	0.0	78	72	0.0	0.0	0.0	--
Sep 78	0.04	73	62	0.04	0.0	0.0	100
Oct 78	1.87	72	49	0.37	1.50	2.51	20
Nov 78	3.84	73	40	0.19	3.65	6.09	5
Dec 78	5.90	73	30	0.23	5.67	9.46	4
Jan 79	6.77	72	26	0.15	6.62	11.03	2
Feb 79	6.89	72	18	0.26	6.63	11.05	4
Mar 79	3.57	71	41	0.38	3.19	5.32	11
Apr 79	2.44	71	48	0.32	2.12	3.53	13
Total	32.40	--	--	2.16	30.24	50.42	--
Average	2.70	73	43	0.18	2.52	4.20	7

*The outdoor ambient temperature sensor (T001) was defective during these months.

subsystems (primarily due to duct leakage) and, to a lesser extent, from the storage tank and the domestic hot water tank. During the primary heating season (October 1978 through April 1979) a total of approximately 4.46 million Btu of solar energy was added to the interior of the house through these various losses. This amount of uncontrolled solar energy added was over two times greater than the measured amount of solar energy supplied to the space heating subsystem during the full 12 month reporting period. As such, this uncontrolled input of solar energy to the house represents a significant contribution to the space heating load.

If the uncontrolled solar energy is added to both the measured space heating load and the solar energy used for space heating, then the heating solar fraction becomes approximately 18 percent for the 12 month reporting period. This is a substantial increase but, even considering the uncontrolled losses, the space heating subsystem performance is still considerably below design expectations.

One final point relating to the uncontrolled solar energy losses should be considered. Even though these losses provide a benefit during the heating season, they represent a burden to the cooling load during the warmer months of the year. If any air conditioning is done, the cost of operating the cooling unit will be increased. If no air conditioning is used, the occupants of the house may still have to suffer some unnecessary discomfort due to higher interior temperature levels.

During the 12 month reporting period a total of 30.24 million Btu of auxiliary energy was consumed by the space heating subsystem. Based on an assumed furnace efficiency of 60 percent, 50.42 million Btu were required to supply the furnace. Using a conversion factor of 140,000 Btu per gallon, approximately 360 gallons of fuel oil were needed to support the space heating subsystem.

4. OPERATING ENERGY

Operating energy for the Fern Tunkhannock 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 and space heating subsystem operating energy. No operating energy is charged against the hot water subsystem because the subsystem operates on a demand basis only and would function regardless of the presence of the solar energy system. 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 Fern Tunkhannock solar energy system is that electrical energy required to operate the blowers in the auxiliary furnace and the energy transport module and the storage loop pumps. These are shown as EP400, EP200 and EP301, respectively, in Figure 2-1. Although additional electrical energy is required to operate the motor driven dampers in the energy transport module 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 12 month reporting period, a total of 5.20 million Btu (1524 kwh) of operating energy was consumed. However, this includes the energy required to operate the blower in the auxiliary furnace, and that energy would be required whether or not the solar energy system was being utilized for space heating. Therefore, the energy consumed by the auxiliary furnace blower 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)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
May 78	0.22	0.12	0.36
Jun 78	0.27	0.02	0.33
Jul 78	0.29	0.01	0.33
Aug 78	0.22	0.0	0.29
Sep 78	0.19	0.02	0.27
Oct 78	0.20	0.27	0.51
Nov 78	0.13	0.34	0.49
Dec 78	0.08	0.43	0.52
Jan 79	0.06	0.44	0.51
Feb 79	0.10	0.48	0.59
Mar 79	0.17	0.34	0.54
Apr 79	0.17	0.26	0.46
Total	2.10	2.73	5.20
Average	0.18	0.23	0.43

A total of 2.86 million Btu (838 kwh) of operating energy was required to support the pumps and fan that are unique to the solar energy system during the reporting period. Of this total, 2.10 million Btu were allocated to the Energy Collection and Storage Subsystem (ECSS) and 0.39 million Btu were allocated to the solar portion of the Space Heating Subsystem. The remaining 0.37 million Btu was not allocated to either subsystem because it was consumed during periods of system transition. However, it is included in the total system operating energy. Since a measured 8.01 million Btu of solar energy was delivered to system loads during the reporting period, a total of 0.36 million Btu (105 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 Fern Tunkhannock solar energy system has a fuel oil fired furnace for auxiliary space heating and auxiliary energy for water heating is provided by electricity. For computational purposes the fuel oil furnace is considered to be 60 percent efficient and the electrical hot water heating element is considered to be 100 percent efficient.

Energy savings for the 12 month reporting period are presented in Table 5-1. During this time the system realized a gross electrical energy savings of 5.85 million Btu, which is the amount of solar energy supplied to the hot water subsystem. However, a total of 2.86 million Btu of electrical operating energy was required to support the solar energy system, so the net electrical energy savings were 2.99 million Btu, or 876 kwh. Fossil fuel savings for the reporting period totaled 3.62 million Btu, or 25.9 gallons of fuel oil (based on a heating value of 140,000 Btu per gallon).

It should be noted that all values relating to space heating (fuel oil) savings are based only on the measured solar energy contribution to the space heating load. As discussed in the space heating subsystem section, approximately 4.46 million Btu of solar energy were added to the interior of the house through various losses during the heating season. This uncontrolled addition of solar energy to the house represents an additional savings of approximately 53 gallons of fuel oil, (assuming a 60 percent furnace efficiency), which is over two times the measured fuel oil savings.

TABLE 5-1
ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)		Fossil Energy Savings (Million Btu)	Solar Operating Energy (Million Btu)	Net Savings			Fossil Equivalent At Source (Million Btu)
					Electrical		Fossil	
	Hot Water	Space Heating	Space Heating		Million Btu	kwh	Million Btu	
May 78	0.54	-0.03	0.24	0.24	0.27	79.1	0.24	0.90
Jun 78	0.46	-0.01	0.10	0.30	0.15	43.9	0.10	0.50
Jul 78	0.40	0.0	0.04	0.32	0.08	23.4	0.04	0.27
Aug 78	0.49	0.0	0.0	0.29	0.20	58.6	0.0	0.67
Sep 78	0.47	-0.01	0.07	0.25	0.21	61.5	0.07	0.70
Oct 78	0.47	-0.08	0.61	0.24	0.15	43.9	0.61	0.50
Nov 78	0.38	-0.05	0.32	0.15	0.18	52.7	0.32	0.60
Dec 78	0.39	-0.04	0.38	0.16	0.25	73.2	0.38	0.83
Jan 79	0.46	-0.02	0.26	0.07	0.37	108.4	0.25	1.23
Feb 79	0.48	-0.03	0.44	0.11	0.34	99.6	0.44	1.13
Mar 79	0.72	-0.06	0.63	0.20	0.46	134.8	0.63	1.53
Apr 79	0.59	-0.06	0.53	0.20	0.33	96.7	0.53	1.10
Total	5.85	-0.39	3.62	2.47	2.99	875.8	3.62	9.96
Average	0.49	-0.03	0.30	0.21	0.25	73.0	0.30	0.83

6. MAINTENANCE

A limited amount of maintenance was required at the Fern Tunkhannock site during the 12 month period covered by this report. Only two visits, occurring in October and November 1978, were required.

The first maintenance visit (October 3 through 5, 1978) was made to install a backdraft damper in the duct between the collector array outlet and the existing furnace ducting. Although the damper was successfully installed, the workmanship was not of the best quality. Holes made in the ducting were not sealed and some access covers were not properly replaced. As a result, leakage from the ductwork was excessive.

The second visit was made on November 24, 1978 for the purpose of correcting the defects left from the backdraft damper installation in October. After the access covers were properly installed and the leaks sealed there was a noticeable improvement in collector array performance.

7. SUMMARY AND CONCLUSIONS

During the 12 month reporting period, the measured daily average incident insolation in the plane of the collector array was 1,063 Btu/Ft^2. This was nine percent below the long term daily average of 1,171 Btu/Ft^2. Considering the shading problem, the measured insolation would appear to be an accurate representation of the long term average for the area. During the nine month period from August 1978 through April 1979 the measured average outdoor ambient temperature was 43°F. This was one degree below the long term average of 44°F for the same nine month period. As a result 6,205 heating degree-days were accumulated, as compared to the long-term average of 6,023 heating degree-days.

Both the long term averages for ambient temperature and insolation are derived from data taken at the Scranton-Wilkes Barre airport which is approximately 20 miles east of Tunkhannock. This represents a slight change in the method for determining the long term average insolation, as this was previously computed using the mean of the Binghamton, New York and State College, Pennsylvania weather stations. The new method will provide a higher degree of accuracy.

The solar energy system satisfied 17 percent of the total measured load (hot water plus space heating) during the 12 month reporting period. This was considerably below the design value of 39 percent estimated by Fern Engineering. The reduction in overall system solar fraction was due primarily to the measured performance of the space heating subsystem. The space heating solar fraction for the reporting period was only seven percent. However, the computations do not account for uncontrolled losses of solar energy into the building that result primarily from duct leakage. As discussed in Section 3.2.4, these losses are substantial and provide a considerable reduction in the measured space heating load. If the uncontrolled losses of solar energy are considered, the heating solar fraction becomes approximately 18 percent. This is a significant improvement but it still represents only about one half of the value needed to bring the overall system solar fraction up to 39 percent.

A total of 80.82 million Btu of incident solar energy was measured in the plane of the collector array during the reporting period. The system collected 19.88 million Btu of the available energy, which represents a collector array efficiency of 25 percent. During periods when the collector array was active, a total of 58.73 million Btu was measured in the plane of the collector array. Therefore, the operational collector efficiency was 34 percent.

For the nine month period from August 1978 through April 1979 a total of 7.09 million Btu of solar energy was delivered to the storage tanks. During this same time period 6.00 million Btu were removed from storage for support of the domestic hot water and space heating loads. The majority of this (4.45 million Btu) went to the domestic hot water subsystem and the remainder was used in support of the space heating subsystem. The effective storage heat loss coefficient was 6.6 Btu/Hr-°F, which is very low and indicates a well insulated storage subsystem. The average temperature of storage was 90°F for the nine month period and 94°F for the full 12 month period.

The hot water load for the 12 month reporting period was 12.15 million Btu. A total of 5.85 million Btu of solar energy and 8.72 million Btu of auxiliary energy were supplied to the subsystem, which represents a weighted hot water solar fraction of 44 percent. The average daily consumption of hot water was 53 gallons, delivered at an average temperature of 137°F. A total of 2.42 million Btu was lost from the hot water tank during the reporting period.

The measured space heating load was 32.40 million Btu for the full reporting period. However, the majority of the space heating demand occurred from October 1978 through April 1979. During this seven month primary heating season the measured space heating load was 31.28 million Btu, or 97 percent of the total. The heating solar fraction for the full 12 month period was seven percent, and, for the primary heating season, it was six percent. During the seven month heating season a total of 1.90 million Btu of measured solar energy and 29.38 million Btu of auxiliary thermal energy were delivered to the space heating load, and this energy maintained an average building temperature of 72°F. Based on an assumed average furnace efficiency of 60 percent, the 29.38 million Btu of auxiliary thermal energy supplied to the space heating subsystem represents 48.97 million Btu, or 350 gallons, of fuel oil that were required for support of the space heating load during the primary heating season.

A total of 2.86 million Btu, or 838 kwh, of electrical operating energy was required to support the solar energy system during the 12 month reporting period. This does not include the electrical energy required to operate the fan in the auxiliary furnace. This fan would be required for operation of the space heating subsystem regardless of the presence of the solar energy system.

Fossil energy savings for the 12 month reporting period were 3.62 million Btu, and gross electrical energy savings were 5.85 million Btu. However, when the 2.86 million Btu of electrical operating energy is taken into account, the net electrical energy savings were 2.99 million Btu, or 876 kwh. If a 30 percent efficiency is assumed for power generation and distribution, then the net electrical energy savings translate into a savings of 9.96 million Btu in generating station fuel requirements. It should also be noted that the fossil energy savings are based only on the measured amount of solar energy delivered to the space heating subsystem. As discussed in Section 3.2.4, the fossil energy savings will increase considerably if the uncontrolled solar energy input to the building is considered.

In general, the performance of the Fern Tunkhannock solar energy system did not measure up to design expectations during the May 1978 through April 1979 time period. Although the hot water solar fraction was 44 percent, the overall system solar fraction was degraded significantly by the marginal performance of the space heating subsystem. However, it must be again stressed that the measured heating subsystem performance does not include the uncontrolled addition of solar energy to the building. The problem has been discussed at some length in the applicable sections of this report, and it serves to emphasize the necessity for a high standard of workmanship in solar energy system construction. If the uncontrolled losses could have been reduced to an inconsequantial level, then both the measured system performance and the accuracy of the system analysis would have improved considerably.

One final point should be noted concerning system design. The Fern Tunkhannock solar energy system is somewhat unusual in that it uses air collectors and water storage. Although it is beyond the scope of this report, it would be interesting to compare the performance of this system with one of similar size using rock storage and operating under comparable weather conditions. A rock bin with a heat storage capacity equal to water would have to be approximately three times as large, but the inherent inefficiency of a heat exchanging device between the collector array and storage would be eliminated. This might lead to more satisfactory performance with regard to space heating.

8. 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 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.

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.

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 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 (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.

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 FOSSIL FUEL (HAF) is the amount of fossil energy supplied directly to the subsystem.

- FOSSIL ENERGY SAVINGS (HSVF) is the estimated difference between the fossil energy requirements of an alternative conventional system (carrying the full load) and the actual fossil energy required by the subsystem.

- ELECTRICAL ENERGY SAVINGS (HSVE) is the cost of the operating energy (HOPE) required to support the solar energy portion of the space heating 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 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.
- 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
FERN TUNKHANNOCK

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR FERN TUNKHANNOCK

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

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

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

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

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 an air system ΔH is generally given by

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

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

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

where EP100 is the 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 Fern Tunkhannock 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 AMBIENT TEMPERATURE (°F)

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

AVERAGE BUILDING TEMPERATURE (°F)

$$TB = (1/60) \times \Sigma\ T600 \times \Delta\tau$$

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/FT^2)

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

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)

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

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 STORAGE (BTU)

$$STEI = \Sigma\ [M200 \times HWD\ (T255,\ T205)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE TO SPACE HEATING (BTU)

$$STEOH = \Sigma\ [M201 \times HWD\ (T255,\ T205)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE TO HOT WATER (BTU)

$$STEOHW = \Sigma\ [M300 \times HWD\ (T300,\ T204)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE (BTU)

$$STEO = STEOH + STEOHW$$

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TSTM = (1/60) \times \Sigma\ [(T200 + T201)/2] \times \Delta\tau$$

TOTAL ENERGY USED BY SPACE HEATING SUBSYSTEM (BTU)

$$HEAT = \Sigma\ [(M400 \times (T400 - T600) + M402 \times (T402 - T600)) \times HRF] \times \Delta\tau$$

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

$$CSEO = HEAT + STEOHW$$

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

$$CSEO = STEO$$

WHEN SPACE HEATING FROM STORAGE

$$CSEO = STEOHW$$

ANY OTHER TIME

PUMP AND FAN SOLAR OPERATING ENERGY (BTU)

$$PFOPE = 56.8833 \times \Sigma\ (EP200 + EP301) \times \Delta\tau$$

ECSS OPERATING ENERGY (BTU)

CSOPE = 0.5 x PFOPE

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

CSOPE = PFOPE

WHEN CHARGING STORAGE

SPACE HEATING SUBSYSTEM SOLAR OPERATING ENERGY (BTU)

HOPES = 0.5 x PFOPE

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

HOPES = PFOPE

WHEN SPACE HEATING FROM STORAGE

HOT WATER CONSUMED (GALLONS)

$HWCSM = \Sigma\ WD300 \times \Delta\tau$

HOT WATER LOAD (BTU)

$HWL = \Sigma\ [\dot{M}300 \times HWD(T350, T204)] \times \Delta\tau$

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWSE = STEOHW

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

$HWAE = 56.8833 \times \Sigma\ EP300 \times \Delta\tau$

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

HSE = HEAT

WHEN SYSTEM USING SOLAR ENERGY FOR HEATING

AUXILIARY FOSSIL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

HAT = HEAT

WHEN SYSTEM USING AUXILIARY ENERGY FOR HEATING

OPERATING ENERGY FOR AUXILIARY FURNACE (BTU)

$HOPEA = 56.8833 \times \Sigma\ EP400 \times \Delta\tau$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

HOPE = HOPEA + HOPES

SUPPLY WATER TEMPERATURE (°F)

TSW = T204

HOT WATER TEMPERATURE (°F)

THW = T350

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.

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

SEA = CLAREA x SE

COLLECTED SOLAR ENERGY (BTU/FT^2)

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)/STEI

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

SEL = CSEO

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

AUXILIARY THERMAL ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWAT = HWAE

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = 100 x HWTKSE/(HWTKSE + HWTKAUX)

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

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

HWSVE = HWSE

AUXILIARY FOSSIL FUEL (BTU)

HAF = HAT/0.6

SPACE HEATING LOAD (BTU)

HL = HAT + HSE

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

HSFR = 100 x HSE/HL

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = - HOPES

SPACE HEATING SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

HSVF = HSE/0.6

SYSTEM LOAD (BTU)

SYSL = HL + HWL

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

SFR = (HL x HSFR + HWL x HWSFR)/SYSL

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = PFOPE + HOPEA

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HWAE

AUXILIARY FOSSIL ENERGY TO LOADS

AXF = HAF

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HWSVE - PFOPE

TOTAL FOSSIL ENERGY SAVINGS (BTU)

TSVF = HSVF

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXE + AXF + SECA

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXF + (AXE + SYSOPE) x 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 Assessments and Solar Energy System Performance Evaluations issued by the National Solar Data 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.

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.

SITE: FERN TUNKHANNOCK 101. LOCATION: TUNKHANNOCK PA

ANALYST: D. GREGORY FCHART NO.: 67.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: 15.00 (DEGREES)

LATITUDE: 41.55 (DEGREES) RUN DATE: 6/25/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1243.	451.	0.36478	1.645	746.	1209	0	26.
FEB	1713.	689.	0.40241	1.423	981.	1056	0	27.
MAR	2330.	992.	0.42567	1.192	1182.	899	0	36.
APR	2982.	1338.	0.44880	1.005	1345.	495	0	49.
MAY	3450.	1593.	0.46170	0.886	1411.	219	33	59.
JUN	3643.	1759.	0.48276	0.837	1472.	26	115	68.
JUL	3542.	1748.	0.49342	0.858	1499.	7	230	72.
AUG	3159.	1515.	0.47967	0.954	1445.	18	173	70.
SEP	2562.	1198.	0.46764	1.125	1348.	116	53	63.
OCT	1892.	896.	0.47358	1.393	1246.	391	7	53.
NOV	1352.	491.	0.36271	1.563	766.	726	0	41.
DEC	1116.	369.	0.33039	1.663	613.	1113	0	29.

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.

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