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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR FERN LANSING, LANSING, MICHIGAN

Prepared by

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16. ABSTRACT

This report 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 is one of a series of reports describing the operational and thermal performance of a variety of solar systems installed in Operational Test Sites. The analysis used is based on instrumented system data monitored and collected for at least one full season of operation. The objective of the analysis is to report the long-term field performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The Solar Energy System was designed by Fern Engineering Company, Bourne, Massachusetts to provide space heating and domestic hot water preheating for a 1,300 square foot single-family residence located in Lansing, Michigan. The Solar Energy System consists of a 278 square foot flat-plate air collector subsystem, a three 120-gallon tank storage subsystem, a 40 gallon domestic hot water tank subsystem, a liquid/air heat exchanger, an energy transport module, pumps, controls and heat transfer medium lines. Natural gas provides the auxiliary energy for the space heating (100,000 Btu/hour) and hot water (70,000 Btu/hour) subsystems. The system is shown schematically on Page 3 of the report and has five modes of operation. The report discusses typical system operation, system operating sequence, performance assessment, system performance, subsystems performance (collector array, storage, hot water, space heating), operating energy, energy savings, and maintenance. A brief summary of all pertinent parameters is presented on Page 57 of this report.

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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. This data is archived by MSFC for DOE.

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* Lansing solar energy system was designed to provide both space heating and domestic hot water preheating for a 1,300-square foot single-family residence in Lansing, Michigan. Solar energy collection is accomplished with flat-plate collectors using air as the transport fluid. The collector array has a gross area of 278 square feet and faces south at an angle of 45 degrees from the horizontal. Energy is transferred to and from storage by means of a liquid/air heat exchanger. Storage capacity is 360 gallons of water in the main tanks (three tanks of 120 gallons each) and 40 gallons in the domestic hot water tank. Auxiliary energy for both the hot water and space heating subsystems is provided by natural gas. The hot water heater has an approximate capacity of 70,000 Btu/hour and the space heating furnace is rated at 100,000 Btu/hour. 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. Figure 2-2 is a pictorial view of the Fern Lansing installation.

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 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.

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

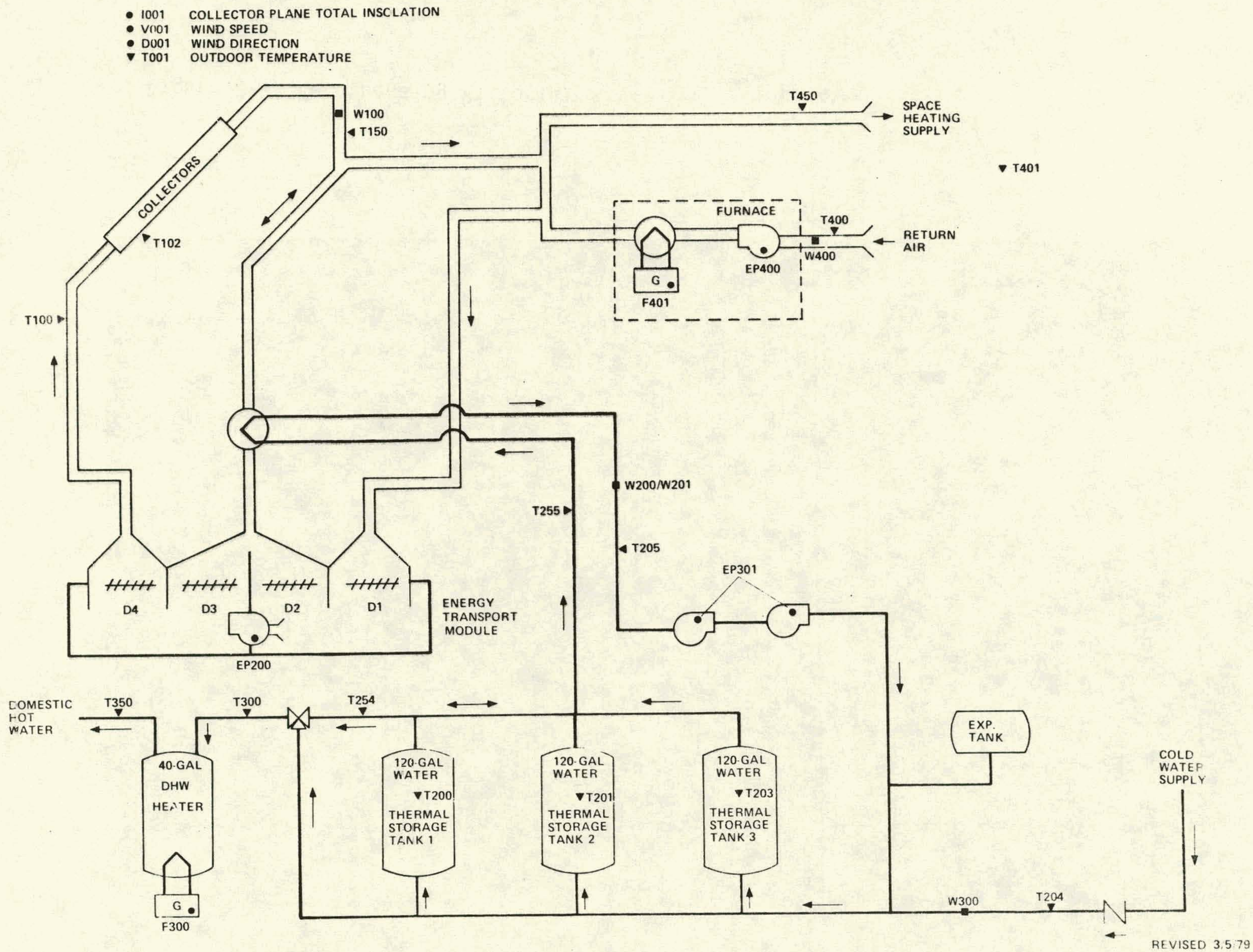


Figure 2-1 Fern Lansing Solar Energy System Schematic

Figure 2-2 Fern Lansing Pictorial

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.

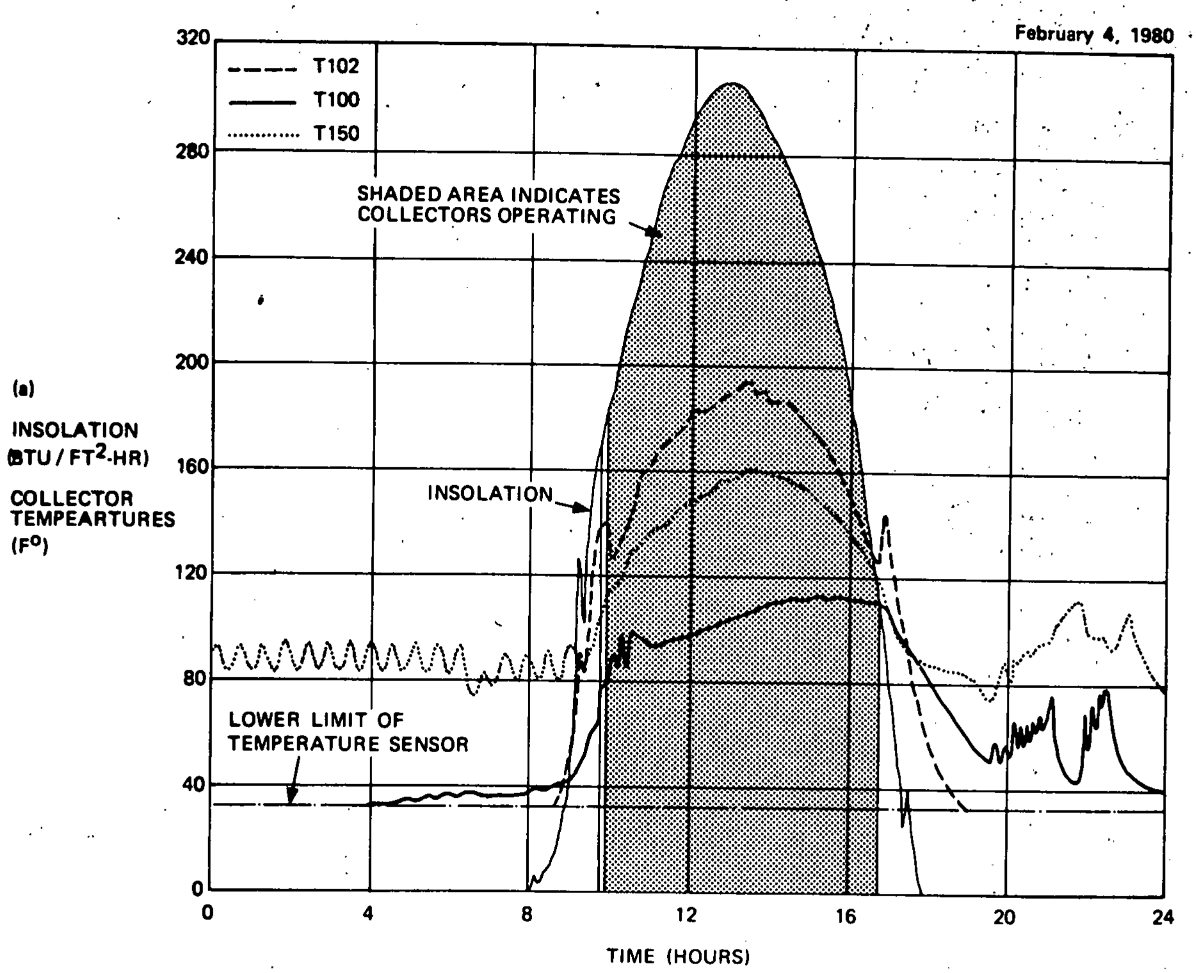
Mode 5 - Collector-to-Storage and Auxiliary Space Heating: This mode is entered whenever the room thermostat is raised 3°F or more above the solar energy system activation temperature, or if the room temperature drops 3°F below the solar energy system activation temperature. Under these circumstances, 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 cold bright day (February 4, 1980) are presented in Figure 2.1-1. Figure 2.1-1 (a) shows the insolation on the collector array and the period when the array was operating (shaded area). Also shown in Figure 2.1-1 (a) are the collector array temperature profiles. These are the inlet temperature (T100), the outlet temperature (T150) and the absorber plate temperature (T102).

On this particular day the collector array cycled on momentarily at 0945 hours and then began normal operation at 0956 hours. At that time the insolation level was 182 Btu/Ft^2-Hr and the absorber plate temperature (T102) was 139°F. At the same time the collector array outlet temperature (T150) was 113°F. Both of these temperatures are higher than the 95°F collector temperature required to initiate direct collector to space heating operation. However, it should be noted that T102 and T150 are not control sensors, but only serve to monitor system behavior. 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 information to determine if each operational mode is functioning within a reasonable range of control temperature sensor limits.

The collector array continued to operate normally through the day. It will be noted that T102 tracked the insolation level quite closely during the operational period. The array outlet temperature (T150) also tracked both the insolation level and absorber plate temperature but its fluctuations were not as pronounced as those of the absorber plate temperature. The collector array inlet temperature (T100) showed a gradual rise almost constantly during the operational period. This is expected because the system was operating in the collector to storage mode most of the day.



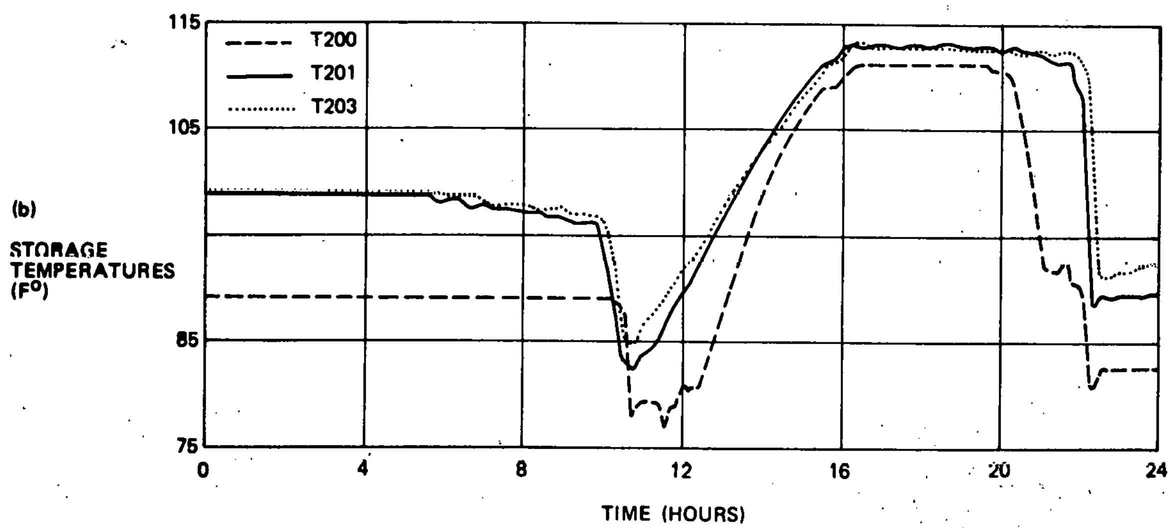


Figure 2.1-1 Typical System Operating Parameters

As a result T100 tended to track the temperature of the storage tanks fairly closely. The only exception to this occurred during the first few minutes of collector array operation. During this time the system cycled between direct space heating and storing solar energy a few times. As a result T100 tended to fluctuate during this time, which is normal.

The collector array continued to operate until approximately 1650 hours when it shut down for the day. At that time the insolation level was 102 Btu/Ft^2-Hr, the absorber plate temperature (T102) was 124°F, and the collector array outlet temperature (T150) was 118°F. The average temperature of the three storage tanks was 112°F at this point, and the average of the collector outlet and absorber plate temperatures was 121°F. The 9°F differential between these average temperatures is somewhat less than the minimum differential of 20°F required to maintain system operation in the collector to storage mode.

Figure 2.1-1 (b) shows the temperature profile of the three 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 tank temperatures remained relatively stable. Although the average temperature for the three 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 0600 hours approximately 22 gallons of hot water was used and a slight temperature fluctuation was noted in tanks two and three. Other smaller water draws continued to cause small temperature drops in the storage tanks until the collector array began operating at approximately 1000 hours. At this point all three tanks exhibited a sharp temperature drop as water began to circulate in the system. This sharp temperature drop occurs because the system is configured so that water is drawn from the top of the tanks and returned to the bottom. As a result cooler water from the bottom portion of the tanks is drawn across the temperature sensors, causing a drop in the indicated tank temperature. Once the system began to operate steadily in the collector to storage mode the tank temperatures began to rise at a relatively constant rate. However, tank one showed some lag due to a heavy demand on the hot water subsystem during the first two hours of storage charging. The average temperature of the storage tanks reached 112°F approximately one half hour before the collector array turned off and they remained at this level for a few hours. However, once hot water and space heating demands began about 1930 hours the tanks were quickly depleted and reached an average temperature of 87°F by 2230 hours. They then remained relatively stable at this temperature for the remainder of the day.

It is difficult to draw any concrete conclusions about the storage subsystem behavior based on the temperature profiles presented in Figure 2.1-1 (b). As noted previously, each 120 gallon tank has only one temperature sensor. Also, the hot water demand at this site was considerably heavier than expected during the latter part of the report period. 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 February 4, 1980. This data correlates with the curves presented in Figure 2.1-1 and provides some additional insight into those curves.

The most important observation to be made from Figure 2.2-1 is the large amount of hot water consumed. On this particular day a total of 219 gallons of hot water was used at the Fern Lansing site (bars without a value above them represent small usages, generally less than one half gallon), and even this large usage was below the monthly average of 237 gallons per day. As a result the solar energy system was able to provide only minimal support to the space heating load. In fact, this day was unusual for the 1979-1980 heating season in that some space heating support was provided by the storage tanks. Generally the heavy hot water consumption kept the storage tank temperatures too low to provide any support to the space heating subsystem.

The second observation to be noted concerns the lack of any measured heating load during the day when the collector array was operating (except briefly early in the operating period). With outdoor ambient temperatures below 40°F all day, a moderate heating load would be expected. The problem here has to do with air leakage in the system. This situation is addressed in greater detail later in this report.

The final point that should be addressed is the large amount of auxiliary energy required to support the domestic hot water subsystem. This large energy usage is due not only to the fact that the hot water load is very substantial, but also 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.

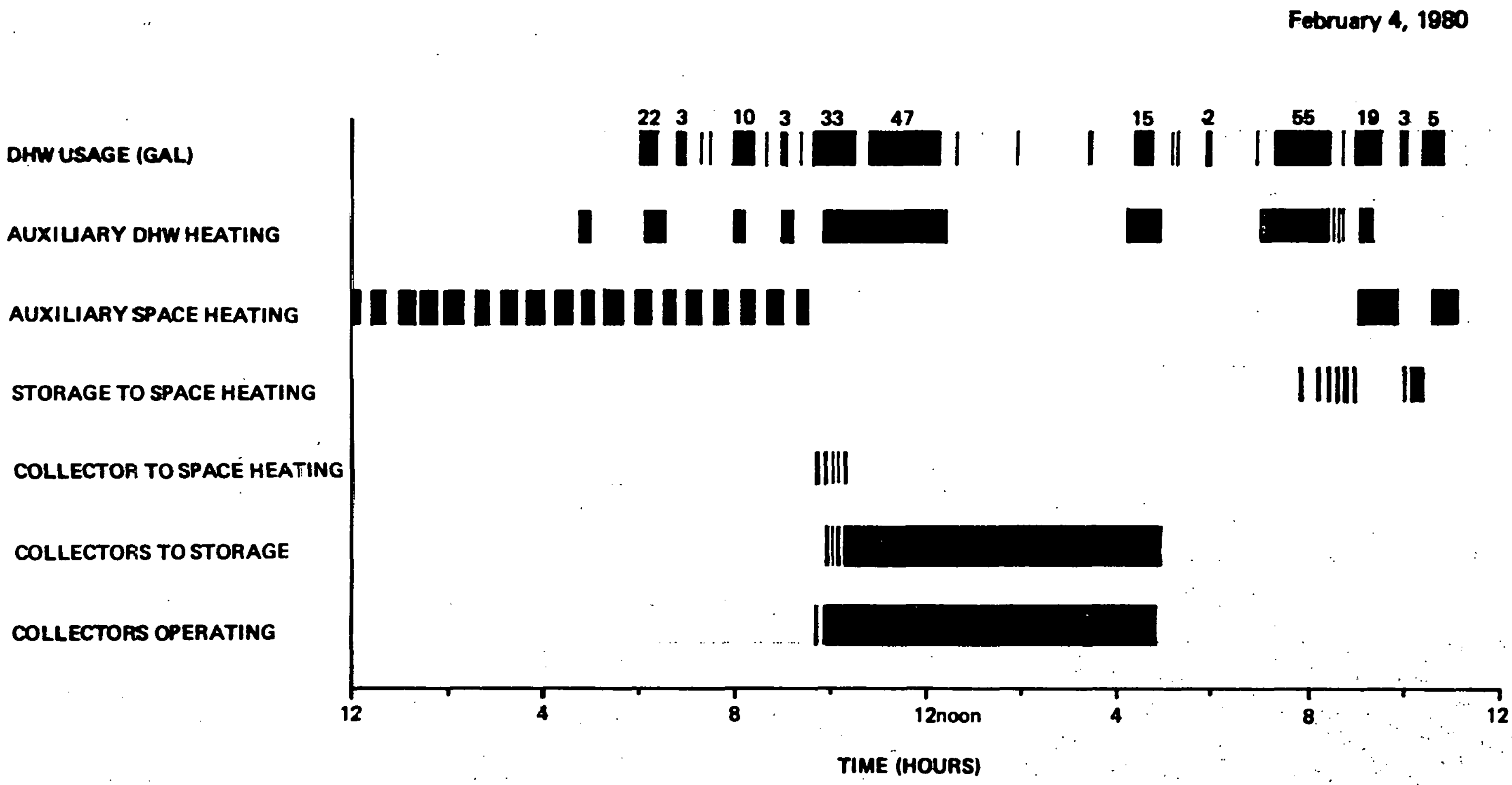


Figure 2.2-1 Typical System Operating Sequence

If a circulation loop was added to the domestic hot water subsystem, the hot water tank would receive more support from the solar energy system. However, 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.

3. PERFORMANCE ASSESSMENT

The performance of the Fern Lansing Solar Energy System has been evaluated for the April, 1979, through March, 1980, time period from two perspectives. The first was the overall system view in which the performance values of system solar fraction and net energy savings were evaluated against the prevailing and long-term average climatic conditions and system loads. The second view presents a more in-depth look at the performance of the individual subsystems. Details relating to the performance of the system are presented first in Section 3.1 followed by the subsystem assessment in Section 3.2.

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

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

The Fern Lansing Solar Energy System was initially brought on line in October, 1977. 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 check-out phase there were several problems noted at the site. These related to both the system itself and the monitoring instrumentation.

The system was found to have some air leakage problems, coupled with low air flow in both the collector and delivery loops. In addition, there were some range and location problems with some of the monitoring instrumentation, so it was not possible to do a significant amount of performance analysis during the 1977-1978 heating season. These problems were cleared up during the spring of 1978, and it was anticipated that detailed site analysis could be performed during the 1978-1979 heating season. However, control problems began to develop in October, 1978, and these resulted in erratic system operation until the controller was replaced in late January, 1979. In addition, it was discovered that there were inadequate backdraft dampers in the system and that the storage loop flow was lower than desirable. These latter two problems were corrected in the February (pump) and March (dampers) time frame but, again, the system performance data for the 1978-1979 heating season was somewhat questionable. As a result, the decision was made to keep the system on line for another year so that system performance data could be gathered during the 1979-1980 heating season.

The preceding information has been presented to provide a brief summary of site operation prior to the start of the performance period covered by this report (April, 1979, to March, 1980). The following paragraphs provide pertinent information concerning site operation during the formal performance reporting period.

The only system problem of any significance noted during the report period was a sticking relay in the storage loop pump control circuit. This relay had to be repaired in April, 1979, and then replaced in August, 1979.

The main area of concern during the report period was the manner in which the system was used. During the first five months (April through August) the system was operated in a normal manner. However, in early September the house was vacated and remained empty until early December. Thus, there were no substantial loads imposed upon either the space heating or domestic hot water subsystems during the early part of the heating season.

When a new family moved into the house in early December the situation changed dramatically. This family used an extremely large amount of hot water (generally over 225 gallons per day) and the hot water load averaged over 7 million Btu per month. As a result, almost all the solar energy collected was used in support of the hot water subsystem. In addition, the temperature of the storage tank was generally lower than the surrounding environment, and this caused heat transfer into the tanks. Thus, for the December, 1979, through March, 1980, time period, the demands imposed on the solar energy system were very different from design expectations.

Based on the foregoing discussion, it must be realized that the final seven months covered in this report (September, 1979, to March, 1980) are not representative of typical solar energy system operation. Therefore, all data for these months should be viewed from that perspective.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the Fern Lansing Solar Energy System located in Lansing, Michigan. 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 April 1979 through March 1980. 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:

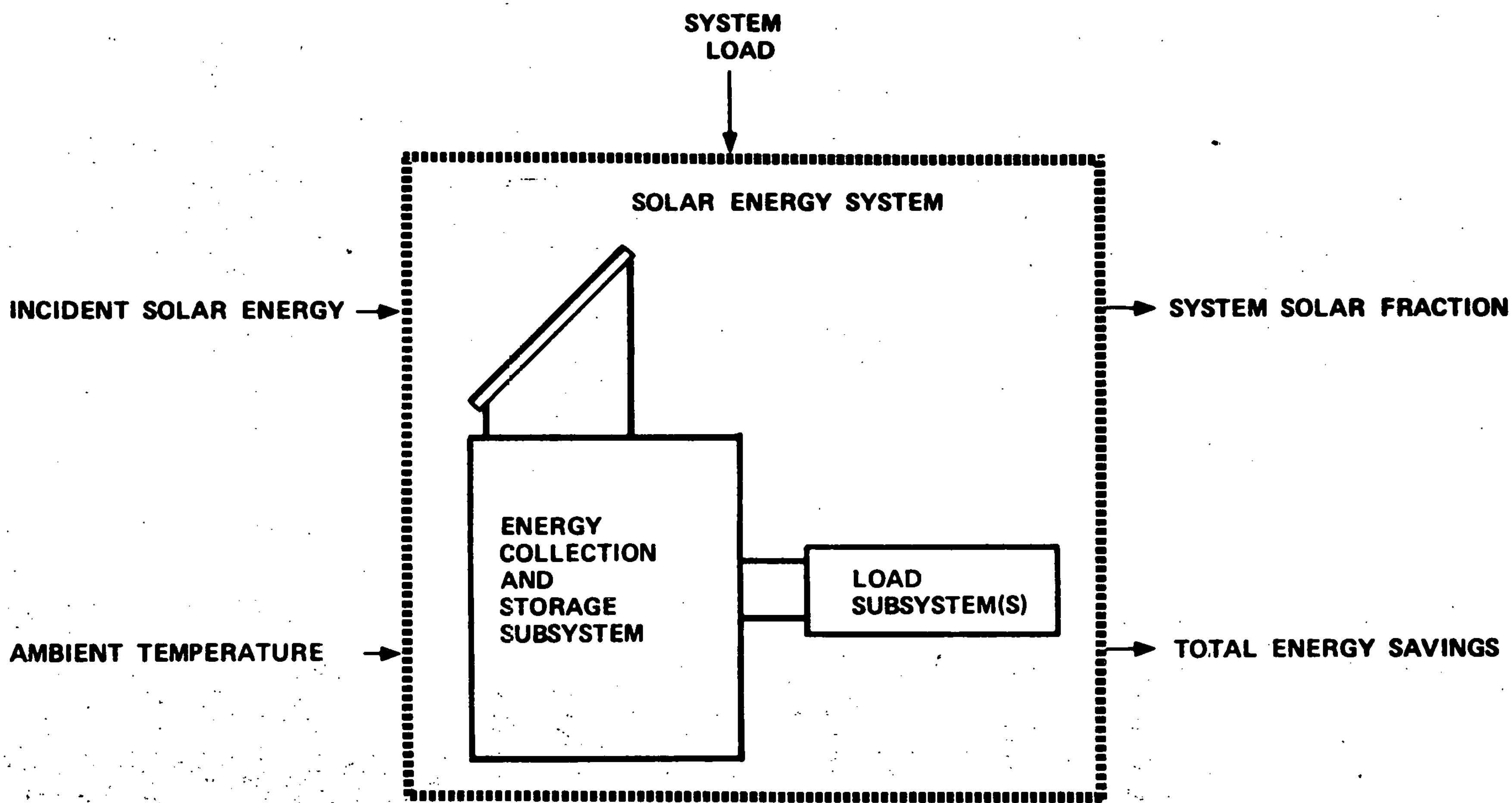


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

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

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

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

Outputs

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

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

The monthly values of the inputs and outputs for the total operational period are shown in Table 3.1-1, the System Performance Summary. Comparative long-term average values of daily incident solar energy, and outdoor ambient temperature are given for reference purposes. The long-term data are taken from Reference 1 of Appendix C. 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

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	
Apr 79	1,198	1,430	45	47	8.10	20	17	2.32
May 79	1,461	1,540	58	58	4.59	27	26	1.92
Jun 79	1,833	1,593	68	68	1.50	67	53	1.61
Jul 79	1,642	1,607	72	72	1.56	70	49	1.68
Aug 79	1,371	1,565	68	71	1.56	64	42	1.46
Sep 79	1,727	1,445	64	63	0.51	74	46	0.39
Oct 79	744	1,237	50	53	1.31	23	12	0.32
Nov 79	693	739	39	40	6.24	17	9	1.47
Dec 79	663	538	32	28	17.58	10	4	2.28
Jan 80	653	636	24	24	21.39	6	3	1.82
Feb 80	874	970	22	26	19.70	8	6	2.21
Mar 80	1,145	1,230	32	34	17.61	14	10	3.38
Total	--	--	--	--	101.65	--	--	20.86
Average	1,167	1,211	48	49	8.47	15*	11	1.74

*Average values of system solar fraction are weighted by the system load.

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 Lansing site for the 12 month report period, the long-term average daily incident solar energy in the plane of the collector was 1,211 Btu/Ft^2. The average daily measured value was 1,167 Btu/Ft^2 which is about four percent below the long-term value. On a monthly basis, October, 1979, was the worst month with an average daily measured value of incident solar energy 40 percent below the long-term average daily value. December, 1979, was the best month with an average daily measured value 23 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 average measured ambient temperature for the 12 month period from April, 1979, through March, 1980, was 48°F at the Fern Lansing site. This compares very favorably with the long-term average value of 49°F.

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. Normally this is illustrated by comparing the performance of the system during the summer (June, July and August) and winter (December, January and February) months. However, as previously noted, the system was not operated in a normal manner during the winter months. The hot water load was so large that very little solar energy was available for support of the space heating subsystem. However, even though the system was operated in an unusual manner, these trends are still evident. 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 eight times higher than during the winter months. However, total savings during the winter were somewhat higher than during the summer and the winter load was much 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 15 percent was somewhat higher than the expected value of 11 percent generated by the modified f-Chart program. Although this variation is significant, it must be realized that the f-Chart prediction model is not ideally suited to the type of system design used at Fern Lansing. For example, the f-Chart model has no provisions to handle a system that uses air collectors and water storage as does the Fern Lansing installation. As a result, the simulation had to be performed using a fully water based system for the comparison model. This causes some differences in the internal f-Chart computational procedures, and this will affect the simulation output. In addition, the unusual load profiles experienced by the system during much of the report period will have a bearing on the situation. Considering these circumstances, the f-Chart predictions for expected solar fraction are not unreasonable, and the overall value of this analysis tool should not be underestimated.

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 Lansing solar energy system was 20.86 million Btu, or 6112 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 Lansing 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 Lansing Solar Energy Installation may be divided into four subsystems:

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

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

3.2.1 Collector Array Subsystem

The Fern Lansing collector array consists of eight Solafern 3000 series flat-plate air collectors arranged in two parallel rows of four in-series collectors each. These collectors are a two-pass air heating type with a single glazing. Typical flowrate through each collector is approximately 305 cubic feet per minute, or 2.19 cubic feet per minute per square foot of gross arrray area. 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:

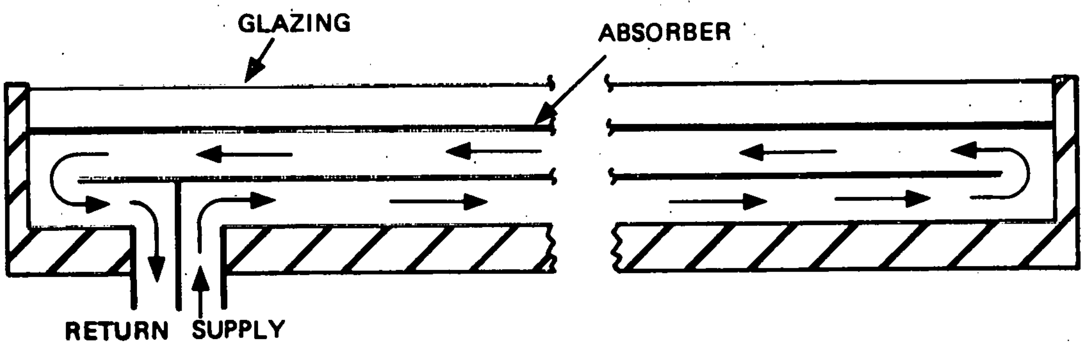
$$\eta_c = Q_s/Q_i \quad (1)$$

where η_c = Collector array efficiency

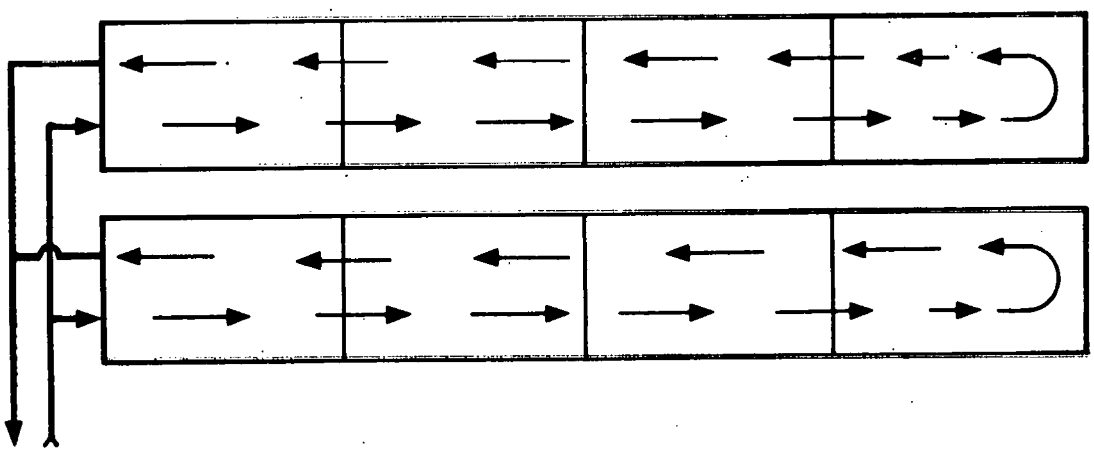
Q_s = Collected solar energy

Q_i = Incident solar energy

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



(a) Collector Air Flow Path



(b) Collector Array Arrangement

COLLECTOR DATA

Manufacturer	– Solarfern, Ltd.
Type of Collector	– Air (3000 Series)
Number of Collectors	– Eight (8)
Flow Paths	– Two (2)
Flow Rate	– 2.19 FT^3/min/FT^2
Cover	– Glass (Single)

SITE DATA

Location	– Lansing, Michigan
Latitude	– 42.78°N
Longitude	– 84.60°W
Collector Tilt	– 45°
Azimuth	– 0°S

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
Apr 79	9.99	3.02	0.30	7.51	0.40
May 79	12.59	3.50	0.28	9.03	0.39
Jun 79	15.29	4.21	0.28	11.79	0.36
Jul 79	14.15	4.22	0.30	11.01	0.38
Aug 79	11.81	3.38	0.29	8.80	0.38
Sep 79	14.40	3.04	0.21	8.47	0.36
Oct 79	6.41	1.37	0.21	3.50	0.39
Nov 79	5.78	1.77	0.31	4.32	0.41
Dec 79	5.72	1.77	0.31	4.34	0.41
Jan 80	5.63	1.31	0.23	3.62	0.36
Feb 80	7.05	1.82	0.26	4.98	0.37
Mar 80	9.87	3.21	0.33	8.05	0.40
Total	118.69	32.62	--	85.42	--
Average	9.89	2.72	0.27	7.12	0.38

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

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

where η_{co} = Operational collector array efficiency

Q_s = Collected solar energy

Q_{oi} = Operational incident solar energy

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

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

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

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

The ASHRAE Standard 93-77 definitions and methods often are adopted by collector manufacturers and independent testing laboratories in evaluating collectors. The collector evaluation performed for this report using the field data indicates that there was some difference between the laboratory single panel collector data and the collector data determined from long-term field measurements. This may or 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 Lansing includes the months from April, 1979, through March, 1980. Although the system was operating prior to April, 1979, these months have not been 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:

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

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

T_i = Collector inlet temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

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

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

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

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

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

b = Intercept on the efficiency axis

$(-)m$ = Slope

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

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

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

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

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

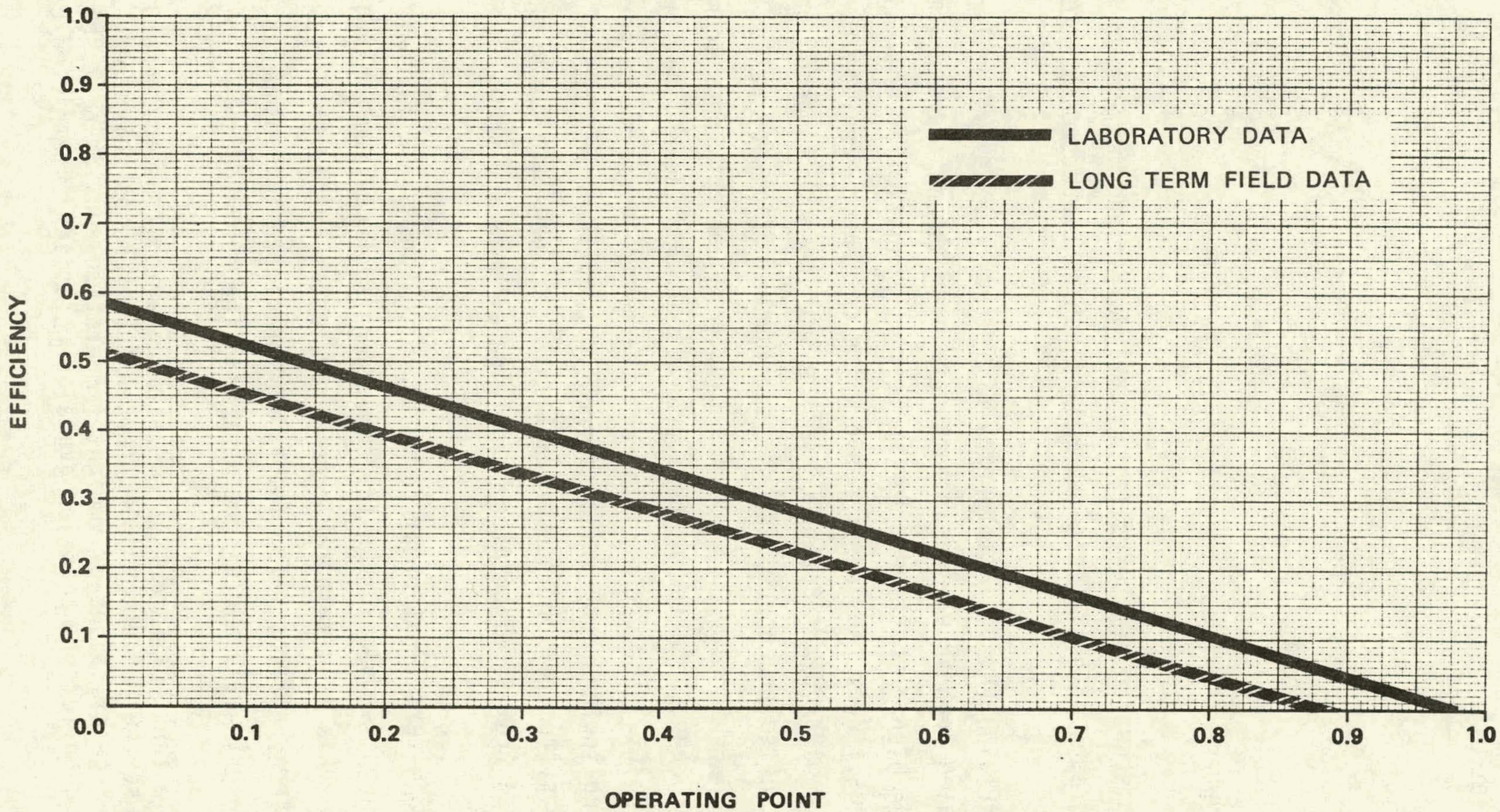


Figure 3.2.1-2 Fern Lansing Collector Efficiency Curves

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:

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

and (6)

$$m = F_R U_L$$

where the terms are as previously defined

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

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

The long-term first order curve shown in Figure 3.2.1-2 has a very 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 extremely close agreement with the curve derived from actual field

*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.

operation. This indicates that the laboratory derived curve might not be too useful for design purposes in an array configuration of this type. However, this statement must be temperated 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

$F_R(\tau\alpha) = 0.580$ $\qquad$ $F_RU_L = -0.600$

Long-term field data

$F_R(\tau\alpha) = 0.504$ $\qquad$ $F_RU_L = -0.565$

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 LANSING LANSING, MICHIGAN

Month	Collected Solar Energy (Million Btu)	Error	
		Field Derived Long-Term	Laboratory Single Panel
Apr 79	2.992	0.026	-0.125
May 79	3.489	0.027	-0.143
Jun 79	2.899	-0.002	-0.180
Jul 79	4.136	0.043	-0.129
Aug 79	3.362	0.035	-0.131
Sep 79	3.030	0.059	-0.124
Oct 79	1.358	0.071	-0.102
Nov 79	1.691	0.109	-0.067
Dec 79	1.683	0.130	-0.049
Jan 80	1.299	-0.001	-0.160
Feb 80	1.809	0.074	-0.099
Mar 80	2.899	0.088	-0.070
Average	2.554	0.050	-0.121

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:

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

where A = Measured solar energy collected
P = Predicted solar energy collected

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

The values of "Collected Solar Energy" given in Table 3.2.1-2 are not necessarily identical with the values of "Collected Solar Energy" given in Table 3.2.1-1. Any variations are due 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.

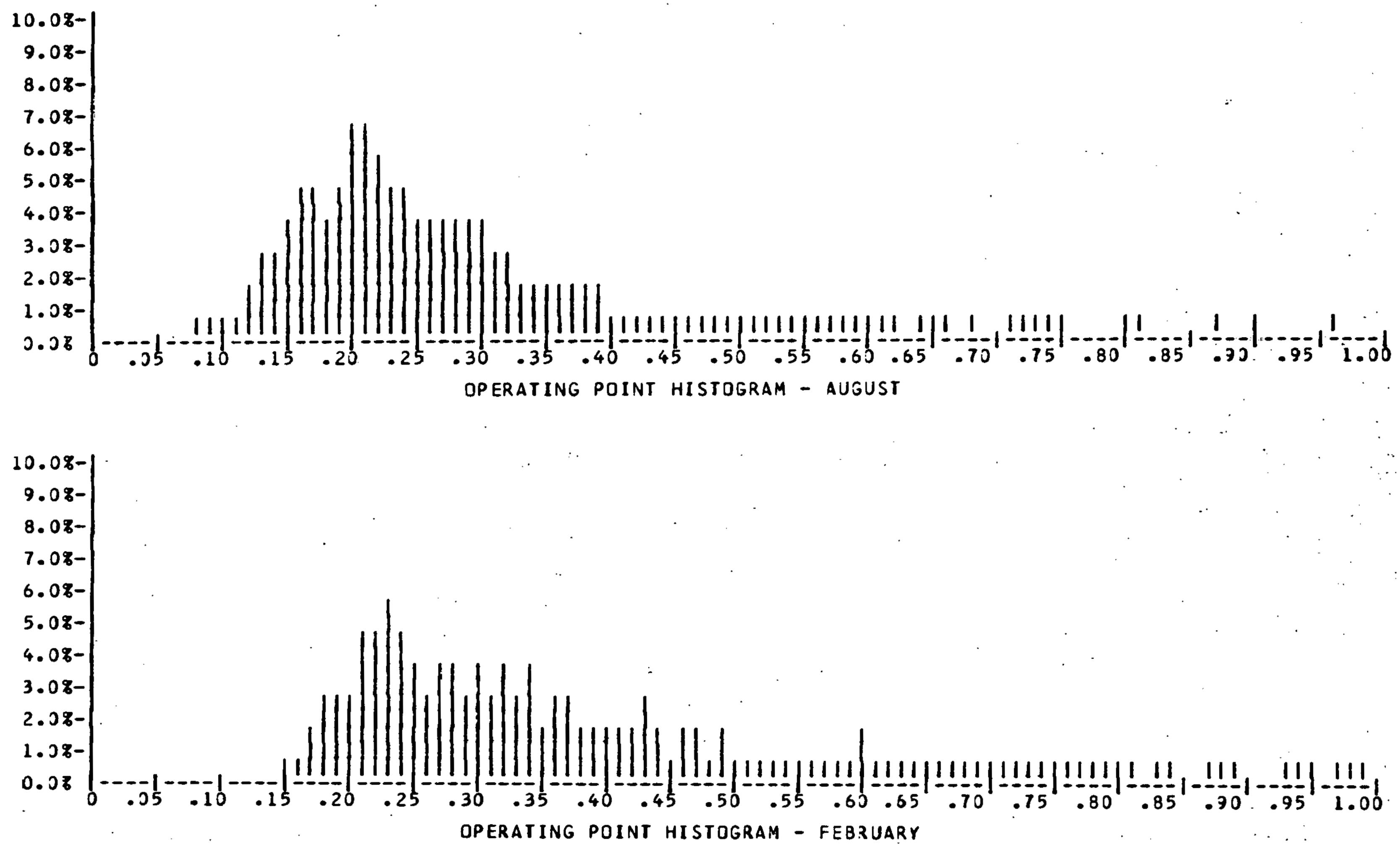
The data from Table 3.2.1-2 illustrates that for the Fern Lansing site the average error computed from the difference between the measured solar energy collected and the predicted solar energy collected based on the field derived long-term collector array efficiency curve was 5.0 percent. For the curve derived from the laboratory single panel data, the error was -12.1 percent. Thus the long-term collector array efficiency curve gives somewhat better results than the laboratory single panel curve in terms of fitting a performance curve to the data.

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 0.28 and for August at 0.22. 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

FERN LANSING LANSING, MICHIGAN

COLLECTOR TYPE: SOLAFERN, LTD. COLLECTOR MODEL: 3000 SERIES



ABSCISSA = (INLET TEMP - AMBIENT TEMP)/INSOLATION DEG F - HR - SQFT/BTU
ORDINATE = PERCENT OF TOTAL OCCURRENCES

Figure 3.2.1-3 Fern Lansing 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 41 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

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

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.

The performance of the Fern Lansing storage subsystem is presented in Table 3.2.2-1. However, as noted previously, the final few months of the reporting period are not representative of typical system operation. This should be kept in mind when reviewing the data for this period, especially the efficiency terms.

During the reporting period a total of 13.78 million Btu was delivered to the storage tanks and 13.40 million Btu were removed for support of system loads. The net change in stored energy for this period was -0.19 million Btu, which leads to a storage efficiency of 0.96 and a total energy loss from storage of 0.57 million Btu.

There are two other points that should be made concerning the storage subsystem performance at Fern Lansing. The first concerns a relay problem in the circuit that controls the storage loop pumps. There were numerous occasions during the first five months of the reporting period when this relay would stick on. As a result, fluid would be circulated between the storage tanks and the heat exchanger in the energy transport module, even though there was no requirement for space heating from storage. Software adjustments were made to minimize the error introduced in the storage subsystem computations by this relay problem, but there are still some inaccuracies present in the energy to and from storage parameters, as well as the storage efficiency computation.

The second point relates to the physical configuration of the pumps in the storage transport loop. Inspection of Figure 2-1 will reveal that these two pumps operate in series. This is not the manner in which they were originally installed. The original installation had the two pumps set up in opposition so that only one pump ran at a time, depending on the mode of operation. However, the flow in the loop was lower than desirable with only one pump running, so the series arrangement was instituted in February 1979. The series arrangement worked well to increase the flow, but it does introduce another problem when the system is collecting and storing solar energy. Since flow can only occur in

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)
Apr 79	1.37	1.43	-0.07	0.99	92
May 79	1.54	1.13	0.05	0.78	111
Jun 79	1.42	1.26	-0.10	0.82	135
Jul 79	1.40	1.32	0.07	0.99	132
Aug 79	1.47	1.14	0.03	0.80	124
Sep 79	1.04	0.41	0.04	0.43	150
Oct 79	0.49	0.39	-0.13	0.53	115
Nov 79	0.61	0.78	-0.10	1.10*	91
Dec 79	1.00	1.31	-0.05	1.26*	69
Jan 80	0.84	1.09	0.04	1.34*	61
Feb 80	1.06	1.28	0.05	1.26*	66
Mar 80	1.54	1.86	-0.02	1.20*	74
Total	13.78	13.40	-0.19	--	--
Average	1.15	1.12	-0.02	0.96	102

*Storage efficiencies are greater than 1.00 during these months primarily due to the abnormal system usage patterns. However, the fact that each 120 gallon tank has only one sensor also contributes to the problem.

one direction with the series arrangement, hot water is drawn from the top of the tanks anytime there is flow in the loop. This results in a higher temperature at both the inlet to the collectors and the heat exchanger when energy is being stored. In turn, these higher temperatures tend to reduce the efficiencies of these components to some extent.

Based on all of the foregoing discussion, it is somewhat difficult to assess the overall performance of the storage subsystem during the reporting period. However, the data indicates that the system did well, considering these various problems.

3.2.3 Hot Water Subsystem

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

The performance of the Fern Lansing 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.

Before beginning any discussion relating to the performance of the hot water subsystem, it must be emphasized that the system was not operated in a normal manner during the final seven months of the reporting period. This situation has been discussed in prior sections of this report and is mentioned again here as a precautionary measure. Therefore, although the totals and averages presented in the following paragraphs cover the full 12 month reporting period they do not really reflect performance of the system under normal load conditions. However, during the first five months of the reporting period (April, 1979, through August, 1979) the system was operated in what can be construed as a normal manner. The interested reader can derive a more representative,

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Hot Water Parameters				Energy Consumed (Million Btu)			Weighted Solar Fraction (Percent)
	Load (Million Btu)	Gallons Used	Temperatures (°F)		Solar	Auxiliary Thermal	Auxiliary	
			Supply	Delivery				
Apr 79	1.76	2,125	51	144	0.73	1.44	2.39	36
May 79	1.40	1,876	56	141	0.82	1.05	1.75	49
Jun 79	1.20	1,903	64	133	1.09	0.56	0.93	72
Jul 79	1.44	2,361	67	134	1.24	0.62	1.04	72
Aug 79	1.51	2,495	69	135	1.09	0.82	1.36	63
Sep 79	0.32	454	78	137	0.25	0.62	1.04	59
Oct 79	0.03	37	67	141	0.01	0.73	1.22	2
Nov 79	0.35	412	62	148	0.09	0.92	1.53	21
Dec 79	6.73	7,207	52	164	1.30	5.64	8.67	20
Jan 80	7.35	7,594	49	166	1.09	6.42	9.88	15
Feb 80	6.82	6,884	46	166	1.26	5.80	8.92	19
Mar 80	7.34	7,510	45	167	1.86	5.72	8.80	26
Total	36.25	40,858	--	--	10.83	30.34	47.53	--
Average	3.02	3,405	59	148	0.90	2.53	3.96	28

although somewhat abbreviated, picture of system performance by examining only the data for these initial months.

For the 12 month period from April, 1979, through March, 1980, the solar energy system supplied a total of 10.83 million Btu to the hot water load. The total hot water load for this period was 36.25 million Btu, and the weighted average monthly solar fraction was 28 percent.

The monthly average hot water load during the reporting period was 3.02 million Btu. This is based on an average daily consumption of 112 gallons, delivered at an average temperature of 148°F and supplied to the system at an average temperature of 59°F. The temperature of the supply water ranged from a low of 45°F in March, 1980, to a high of 78°F in September, 1979.

Each month an average of 0.90 million Btu of solar energy and 2.53 million Btu of auxiliary thermal energy were supplied to the hot water subsystem. Since the average monthly hot water load was 3.02 million Btu, an average of 0.41 million Btu was lost from the hot water tank each month.

3.2.4 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar enery 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 Lansing space heating subsystem is presented in Table 3.2.4-1. For the 12 month period from April, 1979, through March, 1980, the solar energy system supplied a total of 4.59 million Btu to the space heating load. The total heating load for this period was 65.41 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. However, it must be remembered that the system was not operated in a normal manner during most of the months when any significant space heating requirements existed. Therefore, it is not possible to provide any detailed assessment of the space heating subsystem performance.

It should also 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 Lansing site these solar energy losses

TABLE 3.2.4-1

HEATING SUBSYSTEM PERFORMANCE

Month	Heating Parameters			Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
	Load (Million Btu)	Temperatures (°F)		Solar	Auxiliary Thermal	Auxiliary	
		Building	Outdoor				
Apr 79	6.34	78	45	1.02	5.32	9.74	16
May 79	3.19	79	58	0.58	2.61	4.32	18
Jun 79	0.30	81	68	0.15	0.15	0.97	49
Jul 79	0.12	82	72	0.05	0.07	0.88	40
Aug 79	0.05	79	68	0.05	0	0.02	100
Sep 79	0.19	78	64	0.19	0	0	100
Oct 79	1.28	68	50	0.31	0.97	1.52	24
Nov 79	5.89	69	39	1.00	4.89	7.98	17
Dec 79	10.86	76	32	0.28	10.58	15.74	3
Jan 80	14.04	77	24	0.18	13.86	19.10	1
Feb 80	12.88	77	22	0.29	12.59	17.08	2
Mar 80	10.27	77	32	0.49	9.78	13.01	5
Total	65.41	--	--	4.59	60.82	90.36	--
Average	5.45	77	48	0.38	5.07	7.53	7*

*Measured average solar fraction is weighted by the load.

occur during energy transport between the various 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 through April) a total of approximately 4.69 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 slightly 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 13 percent for the 12 month reporting period. This is almost twice as high as the reported value of seven percent, which is based only on the measured contributions to the space heating load.

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 60.82 million Btu of auxiliary energy was consumed by the space heating subsystem. Based on an approximate average furnace efficiency of 67 percent, 90.36 million Btu were required to supply the furnace. Using a conversion factor of 1,000 Btu per cubic foot, approximately 90,360 cubic feet of natural gas were needed to support the space heating subsystem.

4. OPERATING ENERGY

Operating energy for the Fern Lansing 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 Lansing 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 8.45 million Btu (2476 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)
Apr 79	0.27	0.49	0.95
May 79	0.30	0.29	0.63
Jun 79	0.42	0.61	1.05
Jul 79	0.45	0.91	1.37
Aug 79	0.36	0.05	0.48
Sep 79	0.28	0.25	0.55
Oct 79	0.13	0.13	0.30
Nov 79	0.14	0.45	0.64
Dec 79	0.17	0.40	0.57
Jan 80	0.13	0.46	0.60
Feb 80	0.19	0.44	0.63
Mar 80	0.25	0.42	0.68
Total	3.09	4.90	8.45
Average	0.26	0.41	0.70

A total of 4.09 million Btu (1,198 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, 3.09 million Btu were allocated to the Energy Collection and Storage Subsystem (ECSS) and 0.53 million Btu were allocated to the solar portion of the space heating subsystem. The remaining 0.47 million Btu was not allocated to either subsystem because it was consumed during the periods of system transition. However, it is included in the total system operating energy. Since a measured 15.42 million Btu of solar energy was delivered to system loads during the reporting period, a total of 0.27 million Btu (79 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 Lansing Solar Energy System uses natural gas to support both the auxiliary space heating and auxiliary water heating systems. For computational purposes the furnace is considered to be 60 percent efficient and the hot water heater is considered to be 60 to 65 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 -4.09 million Btu, which was the amount of electrical operating energy required to support the solar energy system. Natural gas savings for the reporting period totaled 24.95 million Btu, or 24,950 cubic feet of natural gas (based on a heating value of 1,000 Btu per cubic foot).

It should be noted that all values relating to space heating (natural gas) savings are based only on the measured solar energy contribution to the space heating load. As discussed in the space heating subsystem section, approximately 4.69 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 7817 cubic feet of natural gas, (assuming a 60 percent furnace efficiency), which is an increase of approximately 31 percent over the measured natural gas savings.

One final point needs to be considered in regard to the natural gas savings values just discussed. As noted above, the furnace efficiency chosen for analysis purposes was 60 percent. However, actual system operation indicated that the furnace efficiency was approximately 67 percent. This higher efficiency would tend to reduce the space heating fossil energy savings (including the loss contribution) down to 13.85 million Btu. In the case of the hot water subsystem, there were two values of efficiency used during the report period. For the months of April through November a value of 60 percent was used. However, after the heavy hot water consumption began in December, the efficiency was changed to 65 percent. This was done to more closely approximate the actual operation of the hot water subsystem.

The Fossil Equivalent at Source accounts for the estimated 30 percent efficiency in the delivery of electrical energy from the generating station (source) to the point of used (load). The Fern Lansing Solar Energy System consumed 4.09 million Btu of electrical energy in its operation which, given the efficiency above, required 13.64 million Btu to generate. Overall this expenditure can be subtracted from the Net Fossil savings of 24.95 million Btu, resulting in a total net savings of 11.31 million Btu, or equivalently 1.9 barrels of oil.

TABLE 5-1

ENERGY SAVINGS

Month	Fossil Energy Savings (Million Btu)		Electrical Energy Savings (Million Btu)	Total 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	
Apr 79	1.22	1.70	-0.14	0.60	-0.60	-176	2.92	-2.00
May 79	1.36	0.96	-0.07	0.41	-0.41	-120	2.33	-1.37
Jun 79	1.81	0.25	-0.01	0.45	-0.45	-132	2.06	-1.50
Jul 79	2.07	0.08	-0.01	0.47	-0.47	-138	2.15	-1.57
Aug 79	1.82	0.08	-0.01	0.44	-0.44	-129	1.90	-1.47
Sep 79	0.41	0.31	-0.03	0.33	-0.33	- 97	0.72	-1.10
Oct 79	0.01	0.52	-0.05	0.21	-0.21	- 62	0.53	-0.70
Nov 79	0.15	1.66	-0.14	0.34	-0.34	-100	1.81	-1.13
Dec 79	2.01	0.46	-0.02	0.19	-0.19	- 56	2.47	-0.63
Jan 80	1.68	0.29	-0.01	0.15	-0.15	- 44	1.97	-0.50
Feb 80	1.94	0.48	-0.02	0.21	-0.21	- 62	2.42	-0.70
Mar 80	2.86	0.81	-0.04	0.29	-0.29	- 85	3.67	-0.97
Total	17.34	7.61	-0.55	4.09	-4.09	-1201	24.95	-13.64
Average	1.45	0.63	-0.05	0.34	-0.34	-100	2.08	-1.14

6.0 MAINTENANCE

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

December 2, 1977

- Tighten belt on energy transport module (ETM) blower
- Replace blown fuse in storage loop pump circuit

December 20, 1977

- Install larger sheave on ETM fan to increase air flow through collector loop
- Install backdraft dampers in collector outlet ducts

March 8, 1977

- Install larger motor on ETM fan to again increase collector air flow rate

November 30 - December 1, 1978

- Check and adjust differential controller

January 25, 1979

- Replace differential controller

February 21-23, 1979 (Combined Fern, MSFC and IBM site visit)

- Seal collector array leaks as much as possible
- Adjust ETM blower
- Modify storage loop pump configuration - pumps were plumbed so that both units would run in series at all times, rather than using one pump for flow into storage and the other pump for flow out of storage.

March 28, 1979

- Install additional backdraft dampers in the ETM and ductwork between solar system and auxiliary system

April 9, 1979

- Repair stuck relay in storage loop pump circuit

August 29, 1979

- Replaced relay in storage loop pump circuit

7. SUMMARY AND CONCLUSIONS

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

During the reporting period, the measured daily average incident insolation in the plane of the collector array was 1,167 Btu/Ft^2. This was three percent below the long-term daily average of 1,211 Btu/Ft^2. During the same period the measured average outdoor ambient temperature was 48°F. This was one degree below the long-term average of 49°F. As a result 6,911 heating degree-days were accumulated, as compared to the long-term average of 6,538 heating degree-days.

The solar energy system satisfied 15 percent of the total measured load (hot water plus space heating) during the 12 month reporting period. This did not agree too closely with the expected value of 11 percent for the entire reporting period. However, it should be recalled that this system did not fit the f-Chart model too well, so the disparity between the measured and expected values is not unreasonable.

A total of 118.69 million Btu of incident solar energy was measured in the plane of the collector array during the reporting period. The system collected 32.62 million Btu of the available energy, which represents a collector array efficiency of 27 percent. During periods when the collector array was active, a total of 85.42 million Btu was measured in the plane of the collector array. Therefore, the operational collector efficiency was 38 percent.

During the reporting period a total of 13.78 million Btu of solar energy was delivered to the storage tanks. During this same time period 13.40 million Btu were removed from storage for support of the domestic hot water and space heating loads. The majority of this (10.83 million Btu) went to the domestic hot water subsystem and the remainder was used in support of the space heating subsystem. Again, it is difficult to accurately assess the storage subsystem performance due to the unusual operating circumstances the overall system underwent during the report period.

The hot water load for the 12 month reporting period was 36.25 million Btu. A total of 10.83 million Btu of solar energy and 30.34 million Btu of auxiliary energy were supplied to the subsystem, which represents a weighted hot water solar fraction of 28 percent. The average daily consumption of hot water was 112 gallons, delivered at an average temperature of 148°F. A total of 4.92 million Btu was lost from the hot water tank during the reporting period. Only during the first five months of the reporting period could the hot water load and consumption profiles be considered normal, or close to design expectations.

The measured space heating load for the reporting period was 65.41 million Btu, the majority of which occurred from October through May. A measured total of 4.59 million Btu of solar energy was supplied to the space heating subsystem, which represents a solar fraction of seven percent. The space heating subsystem received very little support from solar energy during the final four months of the report period due to the very large demands imposed by the hot water subsystem. In addition, uncontrolled inputs of solar energy to the space heating load totalled approximately 4.69 million Btu. The total input of energy (both solar and auxiliary) maintained an average building temperature of 77°F.

A total of 4.09 million Btu, or 1,198 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 24.95 million Btu, and electrical energy savings were -4.09 million Btu. If a 30 percent efficiency is assumed for power generation and distribution, then the electrical energy consumption converts to 13.63 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 somewhat if the uncontrolled solar energy input to the building is considered.

In general, the performance of the Fern Lansing solar energy system was very difficult to assess during the reporting period. This was due to the unusual operating conditions that prevailed during the final seven months and the pump relay problem that was noted occasionally during the first five months. However, even under these adverse conditions, the system managed to save a net total (measured) of approximately 21 million Btu. Had the system been used in a more normal manner, the overall net savings might have been higher.

One final point should be noted concerning system design. The Fern Lansing 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

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 energy supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

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

COLLECTOR ARRAY PERFORMANCE

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

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

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

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

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

STORAGE PERFORMANCE

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

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

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

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

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

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

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow to and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary electrical or fossil fuel, solar energy, and the operating energy for the subsystem. In addition, the solar fraction for the subsystem is tabulated. The load of the subsystem is tabulated and used to compute the estimated electrical and fossil fuel savings of the subsystem. The load of the subsystem is further identified by tabulating the supply water temperature, 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 FOSSIL FUEL (HWAF) is the amount of fossil energy supplied directly to the subsystem.

- FOSSIL ENERGY SAVINGS (HWSVF) 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.

- 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 incident solar energy upon the gross collector array measured at the site.
- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.
- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.
- WIND SPEED (WIND) is the average wind speed measured at the site.
- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR FERN LANSING

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR FERN LANSING

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

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

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

For a liquid system ΔH is generally given by

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

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

For 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

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

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

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

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

II. PERFORMANCE EQUATIONS

The performance equations for Fern Lansing 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)

$$TB = (1/60) \times \Sigma\ T401 \times \Delta\tau$$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

FOR $\pm$ 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)

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

WHEN CHARGING STORAGE

SOLAR ENERGY FROM STORAGE TO SPACE HEATING (BTU)

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

WHEN SPACE HEATING FROM STORAGE

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)

$$TSTM = (1/60) \times \Sigma\ [(T200 + T201 + T203/3] \times \Delta\tau$$

TOTAL ENERGY USED BY SPACE HEATING SUBSYSTEM (BTU)

$$HEAT = \Sigma\ [(M400 \times (T450 - T400) \times HRF] \times \Delta\tau$$

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)

$CSOPE = 0.5 \times PFOPE$

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

$CSOPE = PROPE$

WHEN CHARGING STORAGE

SPACE HEATING SUBSYSTEM SOLAR OPERATING ENERGY (BTU)

$HOPES = 0.5 \times PFOPE$

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)

$HWL = \Sigma \; [M300 \times HWD(T350, T204)] \times \Delta\tau$

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

$HWSE = STEOHW$

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

HOT WATER SUBSYSTEM AUXILIARY FOSSIL FUEL ENERGY (BTU)

HWAF = F300C x 1000

AUXILIARY THERMAL ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWAT = HWAF x HWEFF

HWEFF = 0.60 PRIOR TO DECEMBER 1, 1979 AND 0.65 THEREAFTER

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 SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

HWSVF = HWSE/HWEFF

SPACE HEATING SUBSYSTEM AUXILIARY FOSSIL FUEL ENERGY (BTU)

HAF = F401C x 1000

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 = CSOPE + HOPE

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY FOSSIL ENERGY TO LOADS (BTU)

AXF = HAF + HWAF

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = - PFOPE

TOTAL FOSSIL ENERGY SAVINGS (BTU)

TSVF = HSVF + HWSVF

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXF + SECA

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXF + SYSOPE x 3.33)

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

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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.

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