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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR IBM SYSTEM 1B, CARLSBAD, NEW MEXICO

Prepared by

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Solar Energy

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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 following topics are discussed: system description, performance assessment, operating energy, energy savings, maintenance, summary and conclusions.

The IBM-Carlsbad Solar Energy System is located in a single family residence at Carlsbad Caverns National Park, New Mexico. This hot air solar heating and hot water system consists of 408 square feet of SEPCO, flat plate air collectors, a rock storage bin containing 12 tons of 3/4" to 2 1/2" diameter rocks, an energy transport system, air-to-water heat exchanger, controls and a hot water preheat tank which supplies preheated water to a 52 gallon electric hot water tank. An oil hot-air furnace supplies necessary energy when solar energy is insufficient to supply the space heating load. The system has five different modes of operation and became operational in March, 1978.

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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 has been archived by Marshall Space Flight Center for the Department of Energy.

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].*

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*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The IBM-Carlsbad Solar Energy System is located in a single family residence at Carlsbad Caverns National Park. The collector array consists of 408 square feet (gross area) of flat-plate air collectors facing 28° east of due south at a tilt of 45° to the horizontal. Air is used as the medium for transferring solar energy from the collector array to storage and to space heating. Solar energy is stored in a bin containing approximately 24,000 pounds of 3/4" to 2-1/2" diameter rocks. Solar-heated air passes through a heat exchanger where domestic hot water from an 80-gallon tank is preheated. On hot water demand the preheated water is supplied to a standard 52-gallon hot water heater. An electric heating element in the 52-gallon hot water heater provides the auxiliary energy for water heating. When solar energy is insufficient to supply the space heating load, an oil furnace provides the necessary energy. Figure 2-1 is a schematic of the system. The system has five different modes of operation.

Mode 1 - Collector-to-Load: This mode exists when the collector subsystem provides solar heated air directly to the building. This mode is selected when the collector subsystem is on and the building thermostat calls for heat. DHW is preheated during this mode by turning on the pump whenever the top of the preheat tank falls below 150°F.

Mode 2 - Storage-to-Load: This mode exists when rock storage provides heated air to the building. This mode is selected when the collector subsystem is off, the building thermostat calls for heat and the top of the rock storage is greater than 90°F.

Mode 3 - Auxiliary-to-Load: This mode exists when modes 1 or 2 cannot provide heat and the thermostat calls for heat. The oil furnace provides the necessary auxiliary heat energy.

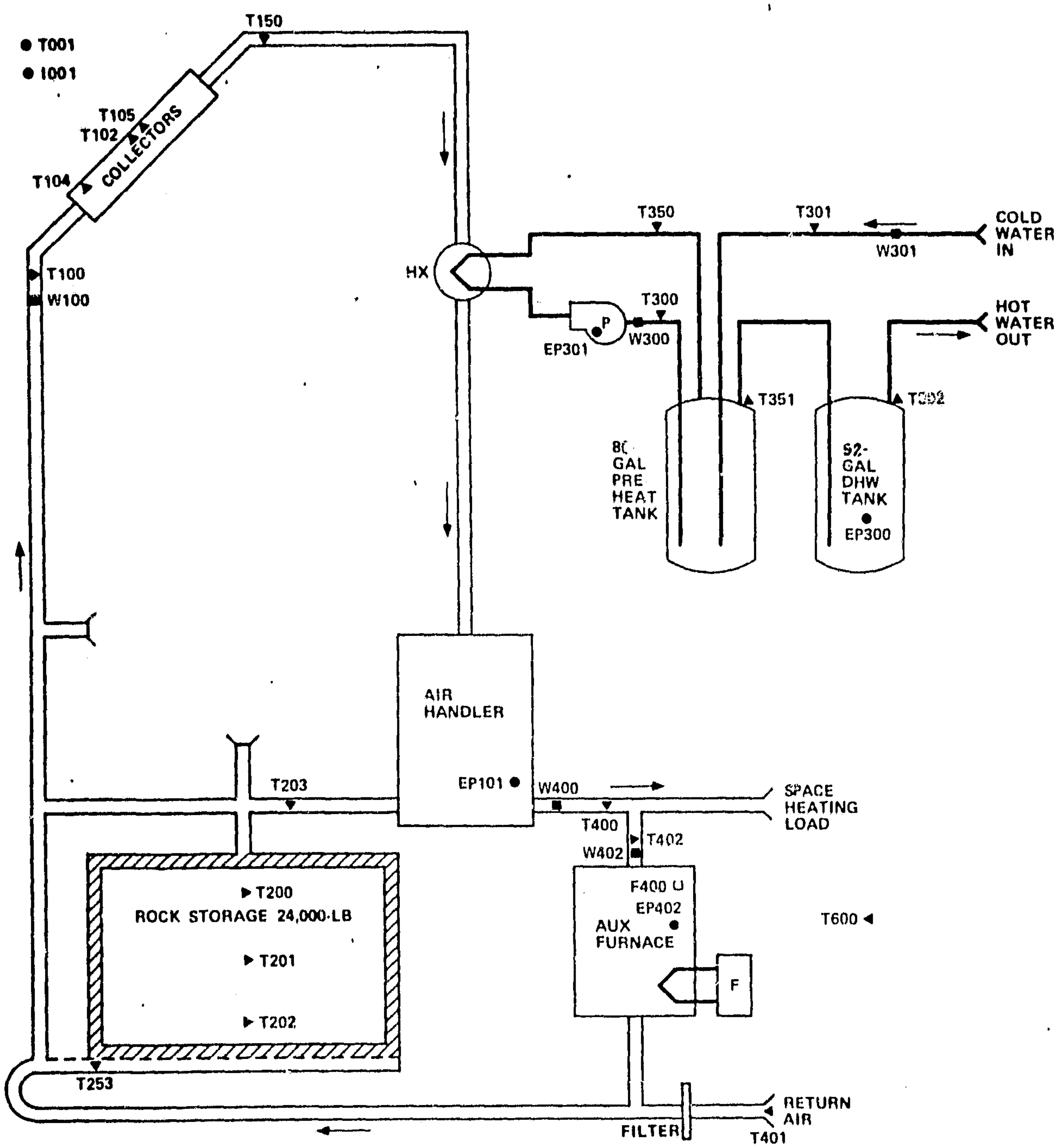


Figure 2-1 IBM System 1B Energy System Schematic

Mode 4 - Collector-to-Storage: This mode exists when solar energy is available but no heat is needed by the building. When the collector outlet temperature is approximately 30°F above the bottom of rock storage, solar heated air is used to charge storage. DHW is preheated during this mode by turning on the pump whenever the top of the preheat tank falls below 150°F.

Mode 5 - Summer Mode: This mode is used during warm weather when solar space heating is not required. Solar heated air is circulated in the collector subsystem to pre-heat the hot water only. In this mode the DHW pump operates simultaneously with the collector blower. During summer mode operation rock storage is bypassed. Operation of this mode starts whenever the collector-to-preheat tank temperature difference exceeds 20°F and stops when this temperature difference drops to 5°F.

2.1 Typical System Operation

Curves depicting typical system operation on a cold clear day (March 17, 1980) are presented in Figure 2.1-1. Figure 2.1-1(a) shows the insolation (I001) on the collector array and the period when the collector array was operating (shaded area). On this particular day the array cycled on and off from 0732 to 0753 and then stayed on continually until 1428. The array cycled on and off three more times between 1428 and 1500 when it turned off for the day. Eleven times during the day (approximately 5 minutes each) collected energy was supplied directly to the house, the balance of the collected energy was supplied to rock storage.

Figure 2.1-1(b) shows typical collector array temperatures during the day. Sun rise was at approximately 0600. From 0600 to 0732 the absorber plate temperature rose from 32°F to 140°F. Collector outlet temperature closely followed the absorber temperature with an average of a 10 degree lag. Collector inlet temperature stayed low throughout the day showing that rock storage removes most of the collected heat energy from the air transport medium.

Figure 2.1-1(c) shows the temperatures at the inlet, top and middle of the rock bed storage. Soon after the system turned on the storage inlet temperature began to rise followed by the rock temperatures. At system shut off the top of rock storage was 125°F and the center was 117°F. The sensor in the bottom of rock storage failed during the year and was not providing data. Storage was sufficiently charged during the day to provide all the necessary space heating through the night.

Figure 2.1-1(d) is a temperature profile of the solar preheated domestic hot water (DHW) as it enters the preheat tank. During this day 127 gallons of hot water were used with 35 gallons being used during the solar collecting period. Water in the 80 gallon preheat tank was 78°F at system turn-on and 120°F at system turn-off. For this day 53 percent of the DHW energy was supplied by solar.

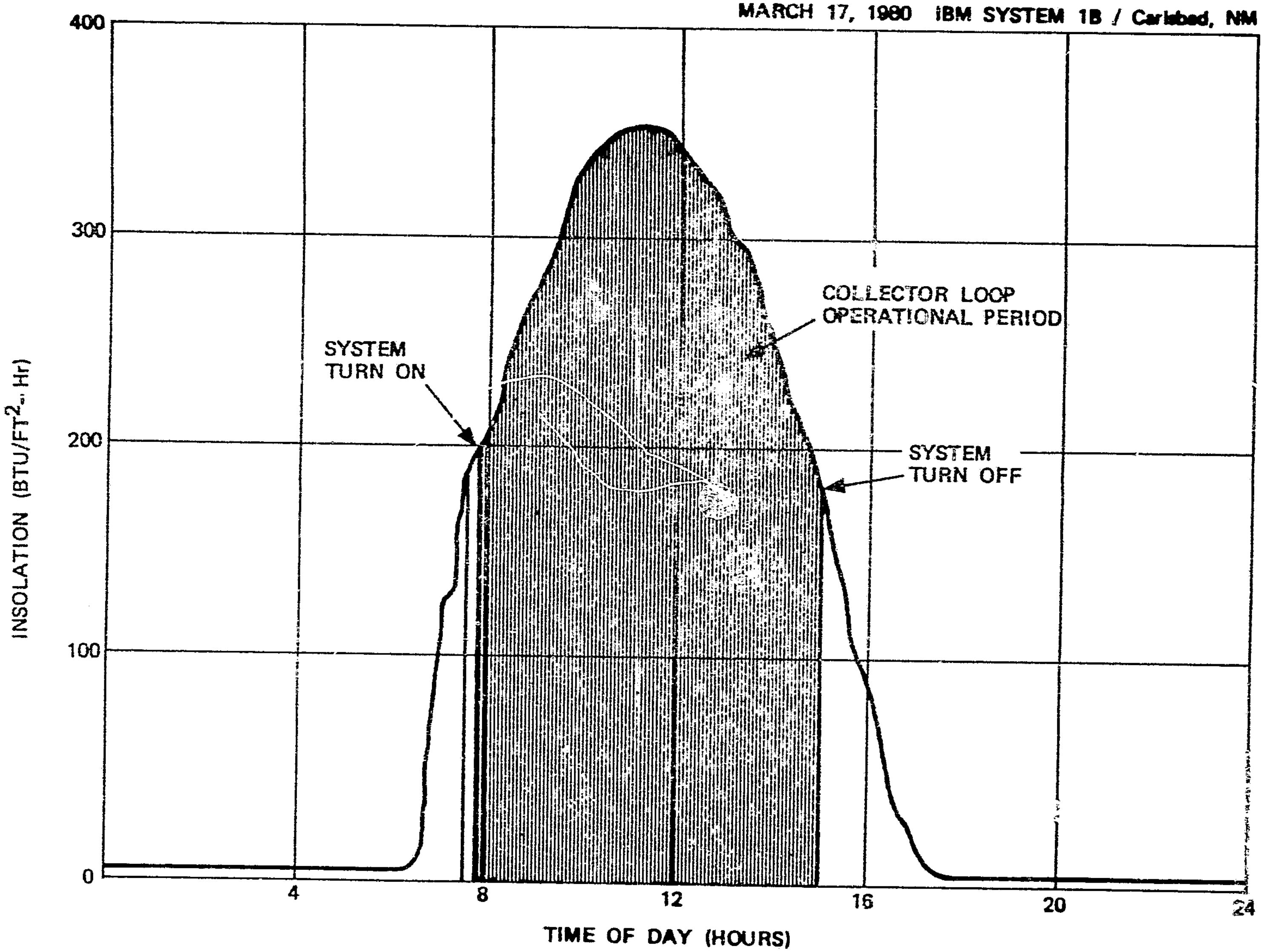


Figure 2.1-1 (a) Solar Insolation vs Time of Day

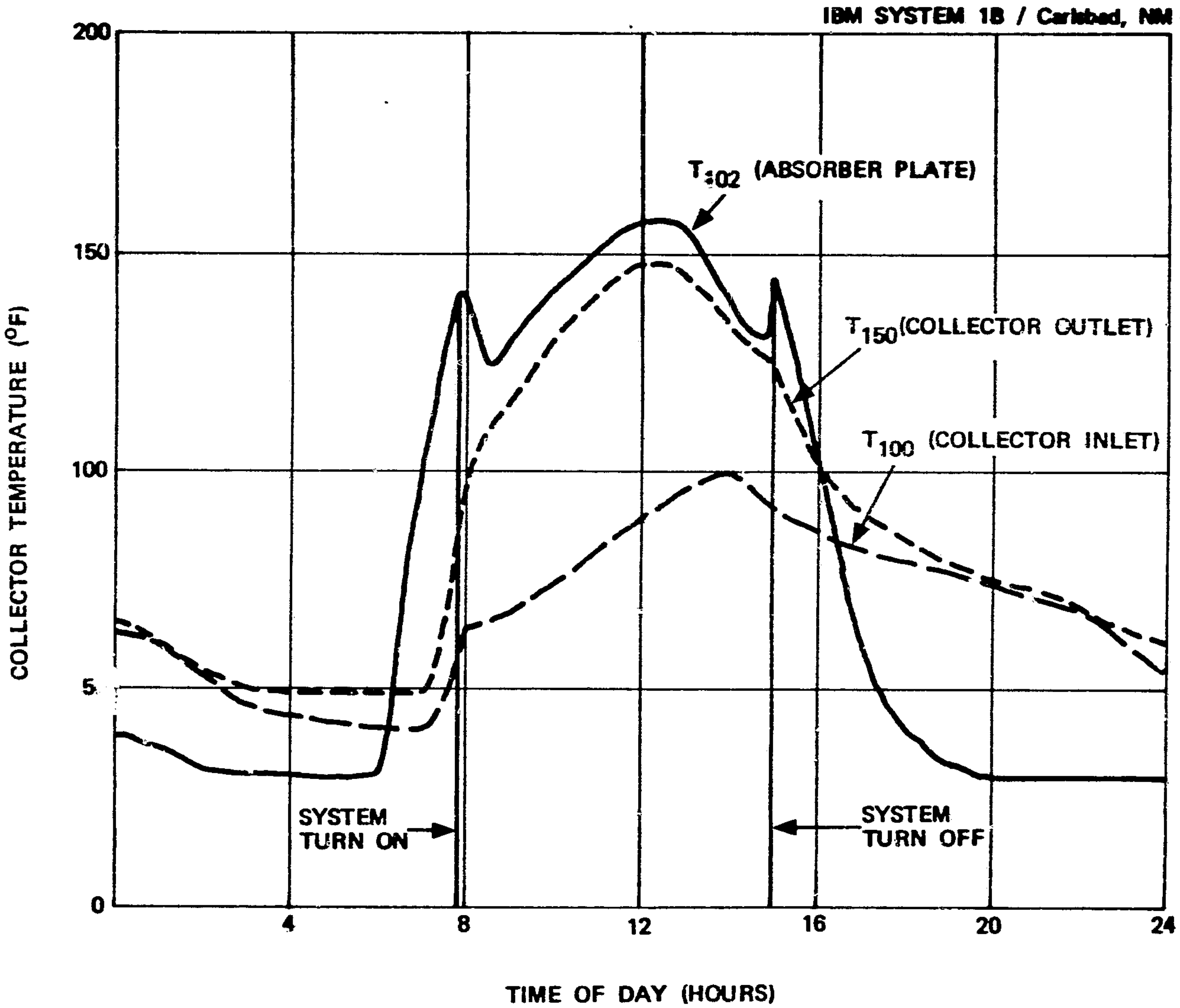


Figure 2.1-1 (b) Collector Temperatures vs Time of Day

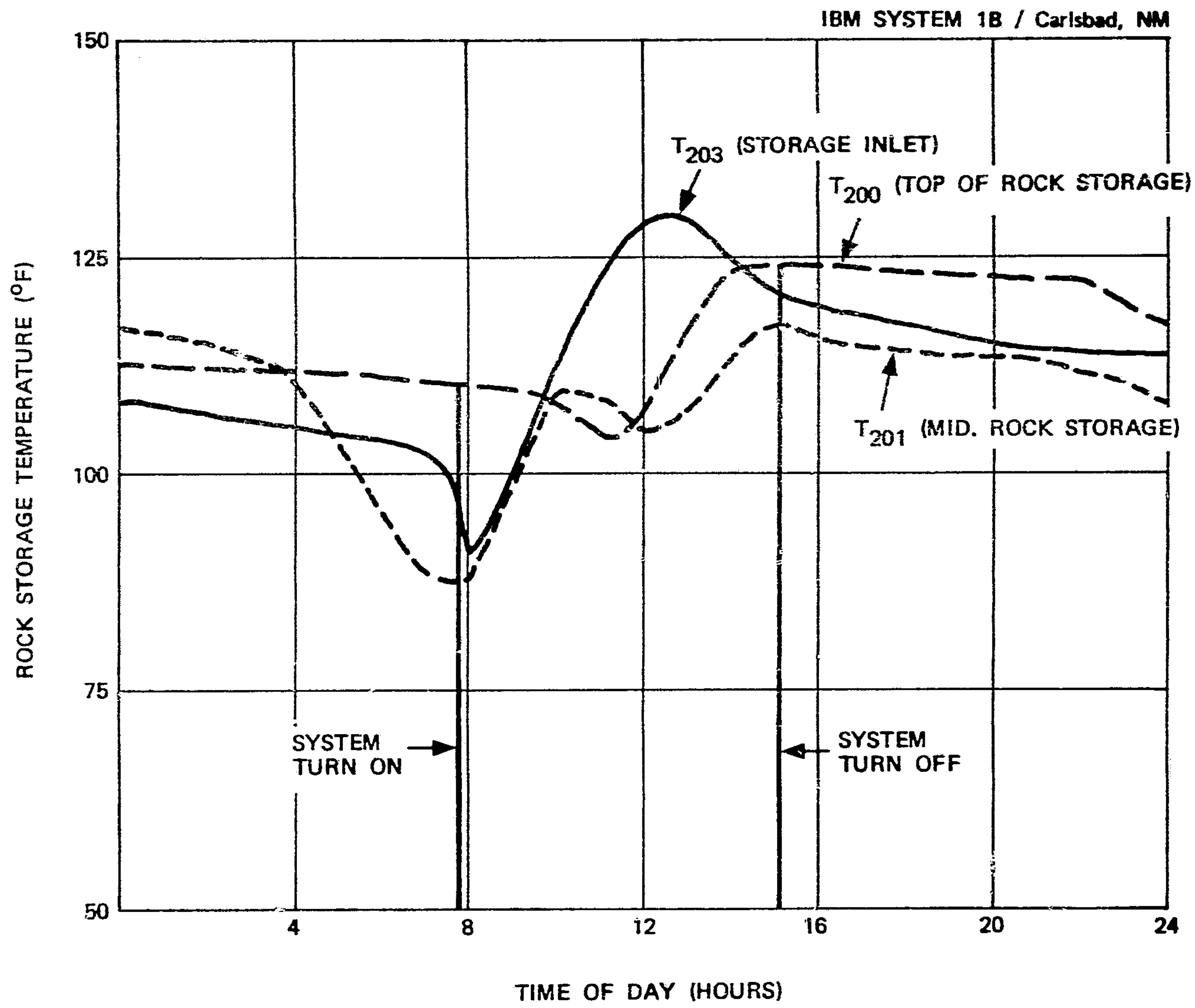


Figure 2.1-1 (c) Collector Temperatures vs Time of Day

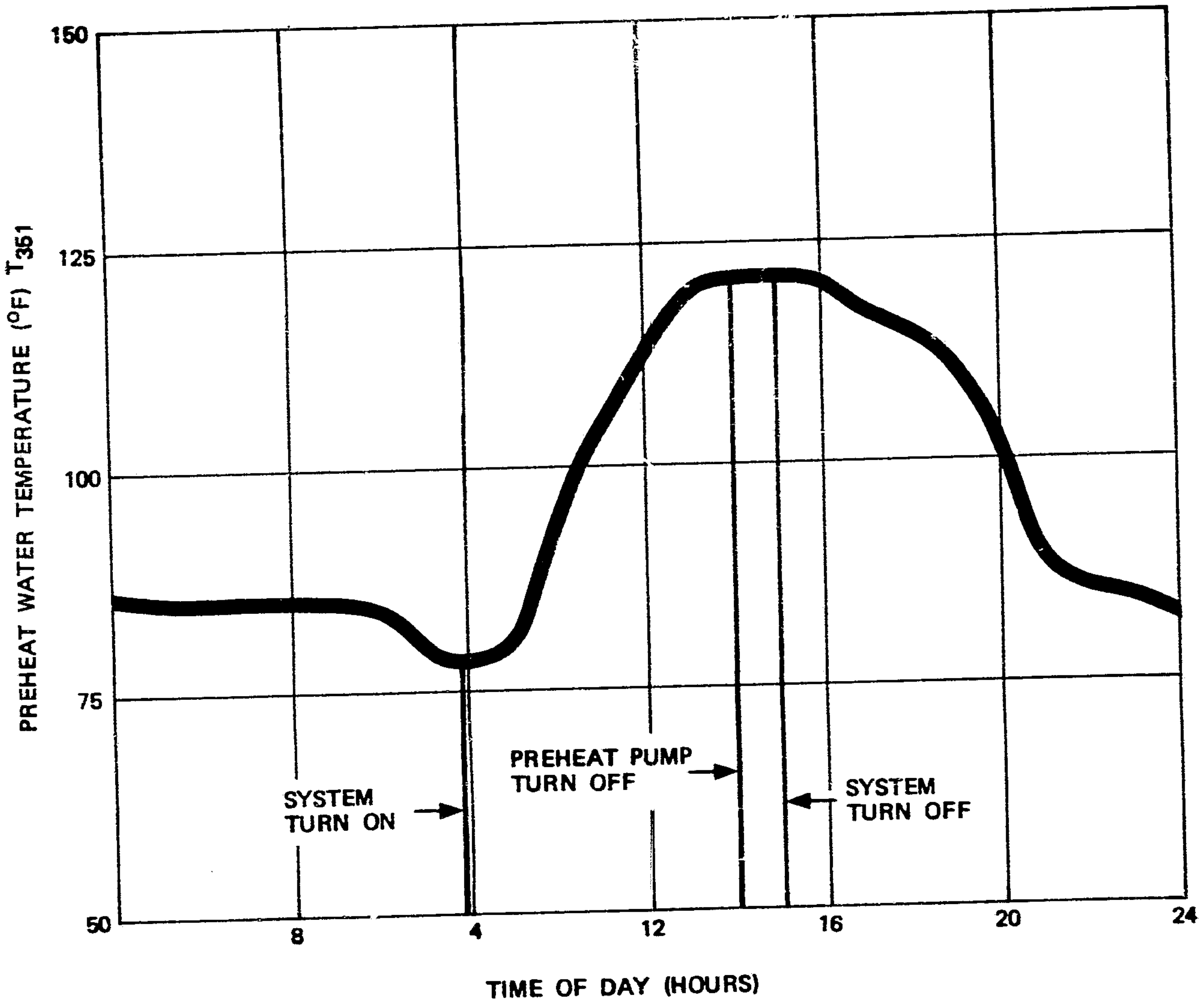


Figure 2.1-1 (d) Preheat Tank Water Temperature vs Time of Day

2.2 Typical System Operating Sequence

Figure 2.2-1 presents bar charts showing typical system operating sequences for March 17, 1980. This data correlates with the curves presented in Figure 2.1-1 and provides some additional insight into those curves.

System heat was required throughout the day with solar able to supply 100 percent of the need. Typically the solar space heating would run for five minutes and be off for 10 to 15 minutes. The solar space heating was supplied from storage when the collector array was not operating and directly from the collector array when it was in operation. Storage was charged continuously during the day except for the periods of time when solar was needed for direct space heating.

Solar energy was used all day to charge the domestic hot water preheat tank. Since the preheat tank water never got above 120°F, some auxiliary heating was required in the DHW heater periodically all day. The DHW usage for the day was 127 gallons, beginning at 0530 in the morning and continuing until 2130. Most of the hot water usage came after the preheat tank had been charged, allowing good utilization of the solar energy. On this day solar supplied 53 percent of the DHW energy and 100 percent of the space heating energy.

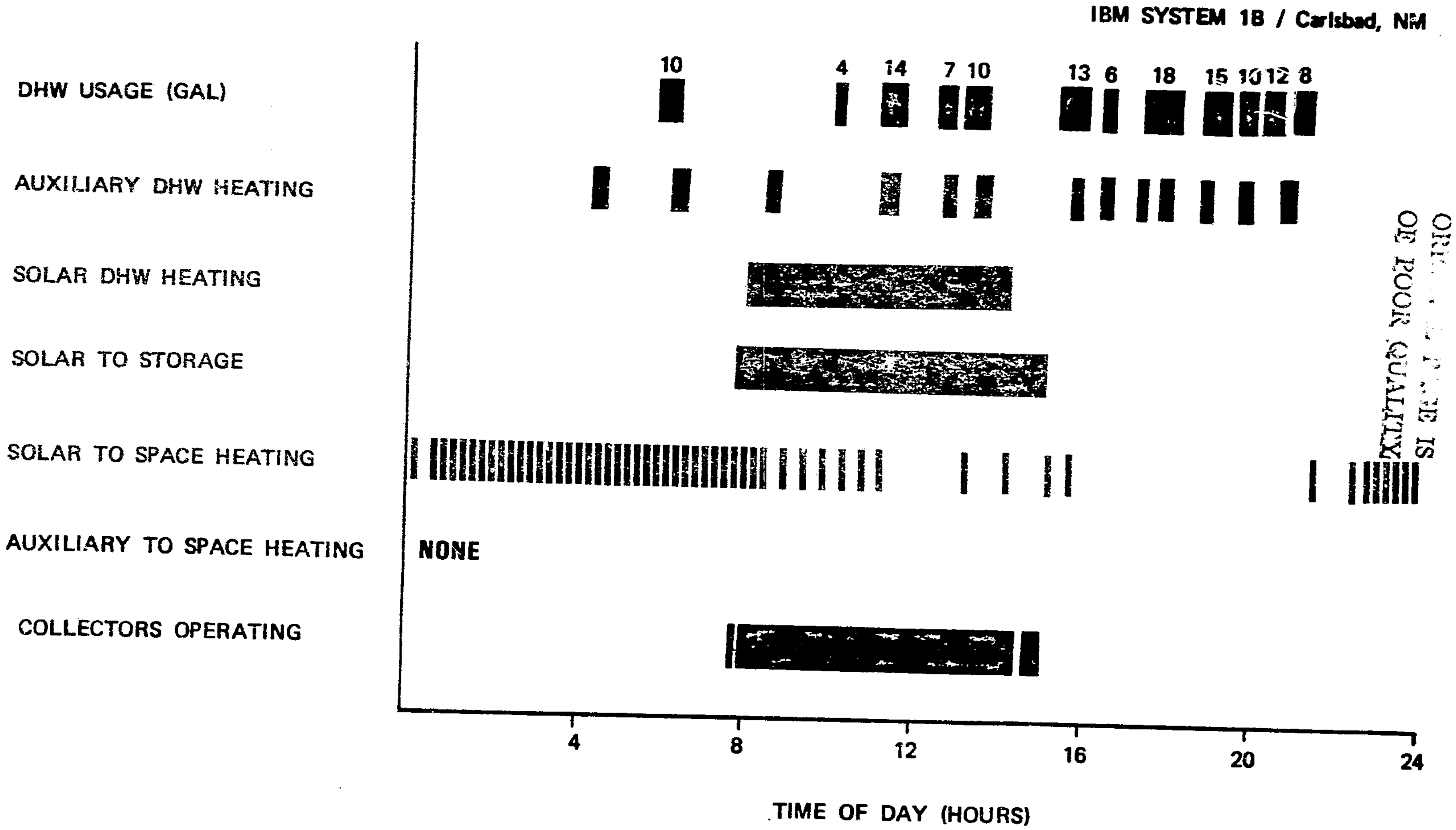


Figure 2.2-1 Typical System Operating Sequence

3. PERFORMANCE ASSESSMENT

The performance of the IBM System 1B Solar Energy System has been evaluated for the April, 1979, through March, 1980, time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load, the measured values for solar energy used and the system solar fraction have been presented. Also presented, where applicable, is the expected value of system solar fraction. The expected value has 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 for designing solar heating systems that was developed by the Solar Energy Laboratory, University of Wisconsin-Madison). The model used in the analysis is based on manufacturers' data and other known system parameters. The second view presents a more in-depth look at the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the domestic hot water subsystem and the space heating subsystem. Included in this are all parameters pertinent to the operation of each individual subsystem.

The performance assessment of any solar energy system is highly dependent on the prevailing climatic conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical climatic parameters has been provided.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the IBM System 1B Solar Energy System located in Carlsbad, New Mexico. 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" [4]. 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) [3] consisting of a remote Site Data Acquisition System (SDAS), telephone data transmission lines and couplers, an IBM System 7 computer for data management, and an IBM System 370/145 computer for data processing. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. These data are processed daily and summarized into monthly performance formats which form a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data given in this report.

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

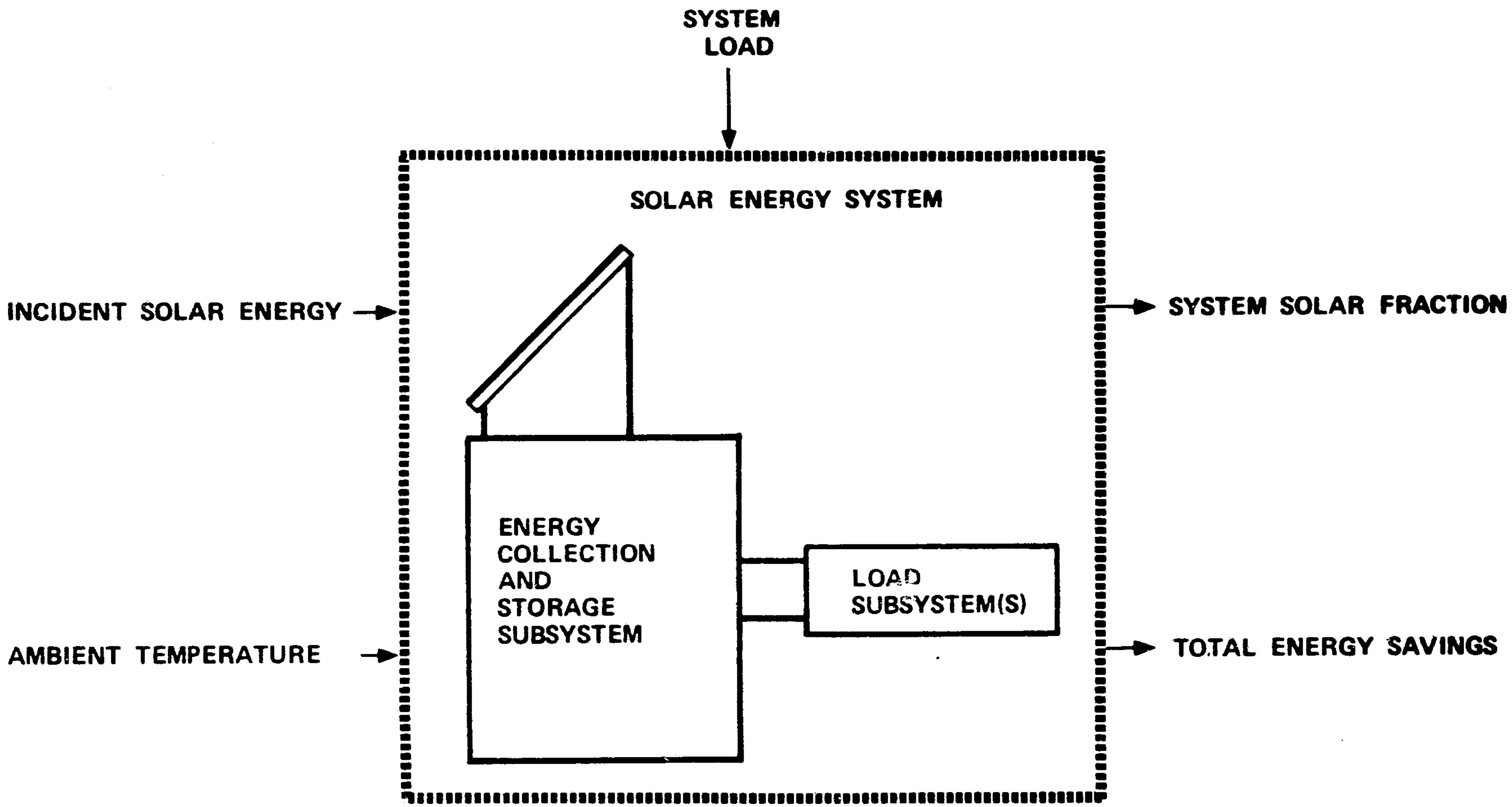


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

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

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

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

Outputs

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

- Total Energy Savings - The quantity of auxiliary energy (electrical or fossil) displaced by the 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 temperatture are given for reference purpose. The long-term data are taken from Reference 1 of Appendix C. Generally the solar energy system is designed to supply an amount of energy that results in a desired value of system solar fraction while operating under climatic conditions that are defined by the long-term average value of daily incident solar energy and

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY

Month	Daily Incident Solar Energy per Unit Area @ 45° Tilt (Btu/ft^2 Day)		Ambient Temperature °F		System Load Measured	Solar Fraction (Percent)		Total Energy Savings
	Measured	Long-Term Average	Measured	Long-Term Average	(Million Btu)	Measured	Expected	(Million Btu)
Apr 79	1960	2194	62	62	2.874	51	77	1.348
May 79	1866	2102	68	71	1.881	64	84	0.737
Jun 79	1731	2051	75	79	1.616	65	86	0.679
Jul 79	1670	1963	79	81	1.076	75	100	0.465
Aug 79	1692	2042	74	80	1.551	72	88	0.777
Sep 79	1834	2057	73	73	1.495	40	80	0.413
Oct 79	2113	2047	68	63	1.818	60	73	0.832
Nov 79	1846	1838	49	50	4.585	65	47	3.698
Dec 79	1647	1669	47	43	6.545	47	34	3.737
Jan 80	1383	1735	47	41	8.509	31	27	3.148
Feb 80	1782	1950	49	46	8.372	29	37	2.870
Mar 80	2056	2154	54	52	5.466	63	57	4.363
Total	21580	23802	--	--	45.79	--	--	23.07
Average	1798	1984	62	62	3.82	48	51	1.92

Averages are weighted values.

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

The measured average daily value for insolation at the IBM System 1B site for the twelve months of the reporting period was 1798 Btu/ft^2. This was 9 percent below the long-term average of 1984 Btu/ft^2.

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 measured average daily ambient temperature was 62°F for the IBM System 1B site which agrees with the long-term value of 62°F. There was negligible adverse impact on system performance due to weather.

The system was designed to deliver 70 percent of an estimated annual space heating load of 57 million Btu and 30 percent of an annual domestic hot water load of 20 million Btu. These values will be discussed in subsequent paragraphs.

The system load was expected to vary in a manner roughly in inverse proportion to the average monthly ambient temperature, other factors remaining constant. During the twelve month reporting period, a total of 45.25 million Btu of solar energy was collected and the total space heating load was 22.65 million Btu (less than one half of the design value) and the domestic hot water load was 21.69 million Btu (8 percent greater than the design value).

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

The measured value of system solar fraction can generally be compared with the expected value so long as the assumptions which are implicit in the f-Chart procedure reasonably apply to the system being analyzed. From Table 3.1-1 the average measured value of 48 percent solar fraction falls short of the average expected value by 3 percentage points, which is reasonably close agreement.

The design value of total system solar fraction based on the 70 percent space heating solar fraction and 30 percent domestic hot water solar fraction is 69 percent. Both the design value and the expected value (Table 3.1-1) were computed using f-Chart. However, it is evident that the modified f-Chart used for the Seasonal Report analysis gave better prediction results. Obviously the more accurate insolation and loads input to modified f-Chart are responsible for this prediction improvement.

The total energy saving is the most important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with less expensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment of the system. In terms of the technical analysis presented in this report the net total energy savings should be a significant positive figure. The total energy savings for the IBM System 1B Solar Energy System was 23.07 million Btu, which is equivalent to 275 gallons of fossil fuel with a conventional system of 60 percent efficiency.

3.2 Subsystem Performance

The IBM System 1B Solar Energy System may be divided into four subsystems:

1. Collector array
2. Storage
3. Heating
4. Hot Water

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 IBM System 1B collector array consists of 17 Solar Energy Products, Model EF-212 flat plate air collectors having a gross area of 408 square feet. Flow details and other pertinent operational characteristics are shown in Figure 3.2.1-1. The collector subsystem analysis and data are given in the following paragraphs.

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

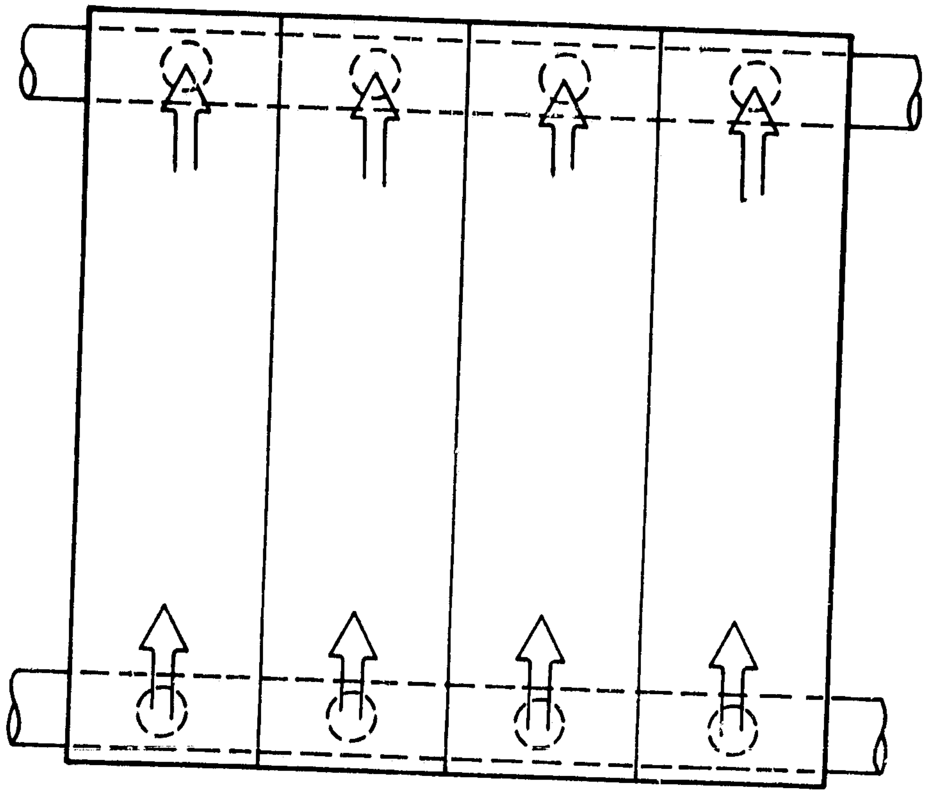
$$\eta_c = Q_s/Q_i \qquad (1)$$

where η_c = Collector array efficiency

Q_s = Collected solar energy

Q_i = Incident solar energy

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



Collector Data

Manufacturer - Solar Energy Products Co.

Model - EF212

Type - Air

Number of Collectors - 17

Flow Paths - 17

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Site Data

Location - Carlsbad, New Mexico

Latitude - 32.5°

Longitude - 104.3°

Collector Tilt - 45°

Azimuth - 28° East of South

Figure 3.2.1-1 Collector Array Schematic

TABLE 3.2.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Apr 79	23.985	3.424	0.143	14.779	0.232
May 79	23.607	2.798	0.119	19.085	0.147
Jun 79	21.183	2.555	0.121	16.880	0.151
Jul 79	21.127	2.310	0.109	15.672	0.147
Aug 79	21.401	2.580	0.121	16.586	0.156
Sep 79	22.452	1.340*	0.060	9.733	0.138
Oct 79	26.720	3.469	0.130	15.265	0.227
Nov 79	22.599	5.905	0.261	18.208	0.324
Dec 79	20.827	5.576	0.268	17.756	0.314
Jan 80	17.490	4.652	0.266	14.335	0.325
Feb 80	21.088	4.085	0.194	15.621	0.262
Mar 80	26.009	6.559	0.254	20.883	0.314
Total	268.488	45.253	--	194.803	
Average	22.374	3.771	0.171	16.234	0.232

*System down for repairs September 26.

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

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

where η_{co} = Operational collector array efficiency

Q_s = Collected solar energy

Q_{oi} = Operational incident solar energy

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

T_i = Collector inlet temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

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

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

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

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

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

b = Intercept on the efficiency axis

$(-)m$ = Slope

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

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

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

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

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

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

$$b = F_R \tau\alpha$$

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 two curves of Figure 3.2.1-2 show the differences that similar analysis studies done on other collectors have shown. The original manufacturer's laboratory performance curve was generated under an outside environment with a flow of 16 pounds/hour/square foot of collector area. The curve shown in Figure 3.2.1-2 was derated for a flow of 9 pounds/hour/square foot of collector area. The long-term field data curve was also generated with a flow of 9 pounds/hour/square foot of collector area according to Reference [5].

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

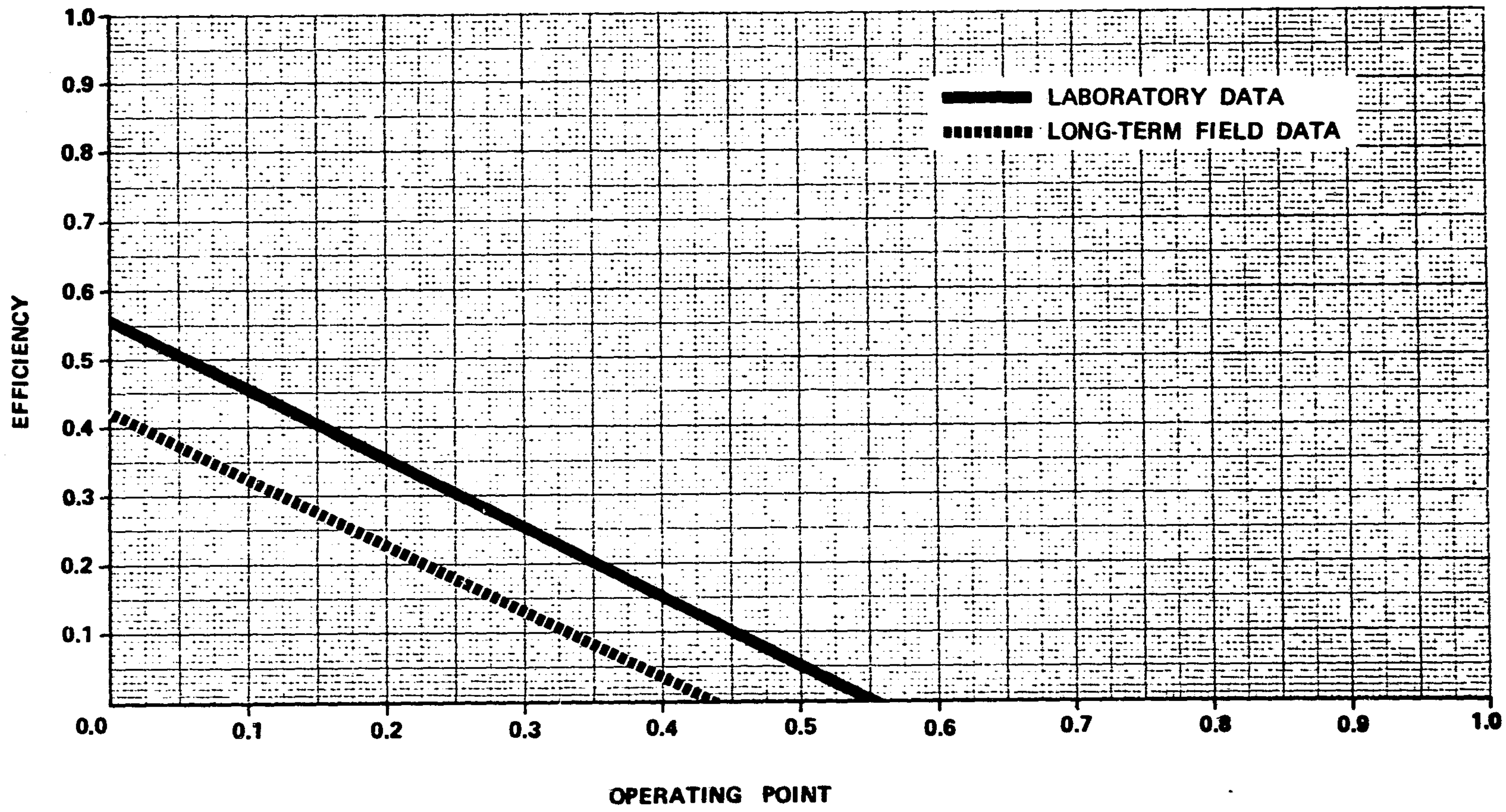

Figure 3.2.1-2 IBM System 1B Collector Efficiency Curves

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

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

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

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

   b. The laboratory single panel collector efficiency curve

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

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

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

where A = Measured solar energy collected

P = Predicted solar energy collected

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

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: IBM SYSTEM LB

Huntsville, Alabama

MONTH/YEAR	COLLECTED SOLAR ENERGY (MILLION BTU)	ERROR	
		FIELD DERIVED LONG-TERM	LAB PANEL
Apr 79	3.324	-0.041	-0.301
May 79	2.741	-0.037	-0.466
Jun 79	2.512	-0.029	-0.458
Jul 79	2.242	-0.049	-0.466
Aug 79	2.566	-0.016	-0.436
Sep 79	0.000	-0.000	0.000
Oct 79	3.454	-0.172	-0.437
Nov 79	5.491	-0.007	-0.231
Dec 79	5.364	-0.065	-0.334
Jan 80	4.223	-0.069	-0.339
Feb 80	0.000	-0.000	0.000
Mar 79	6.368	+0.012	-0.202
Average	3.829	-0.041	-0.343

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

The data from Table 3.2.1-2 illustrates that for the IBM System 1B 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 4.1 percent. For the curve derived from the laboratory single panel data, the error was 34.3 percent. Thus the long-term collector array efficiency curve gives worse results than the manufacturer's laboratory single panel curve.

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

Another characteristic of the operating point histogram is the shifting of the distribution along the operating point axis. This can be explained in terms of the characteristics of the system and the climatic factors of the site, i.e., incident solar energy and ambient temperature. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (January) and a typical summer month (July) operation. The actual midpoint which represents the average operating point for January is at 0.06 and for July at 0.28.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the 12 month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equations (1) and (2). The values of operational collector efficiency range from a maximum of 0.325 in January, 1980 to a minimum of 0.14 in September, 1979. The operational collector array efficiency exceeded the collector array efficiency which included the effect of the control system by approximately 36 percent.

Additional information concerning collector array analysis in general may be found in Reference [7]. The mate ,al 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.

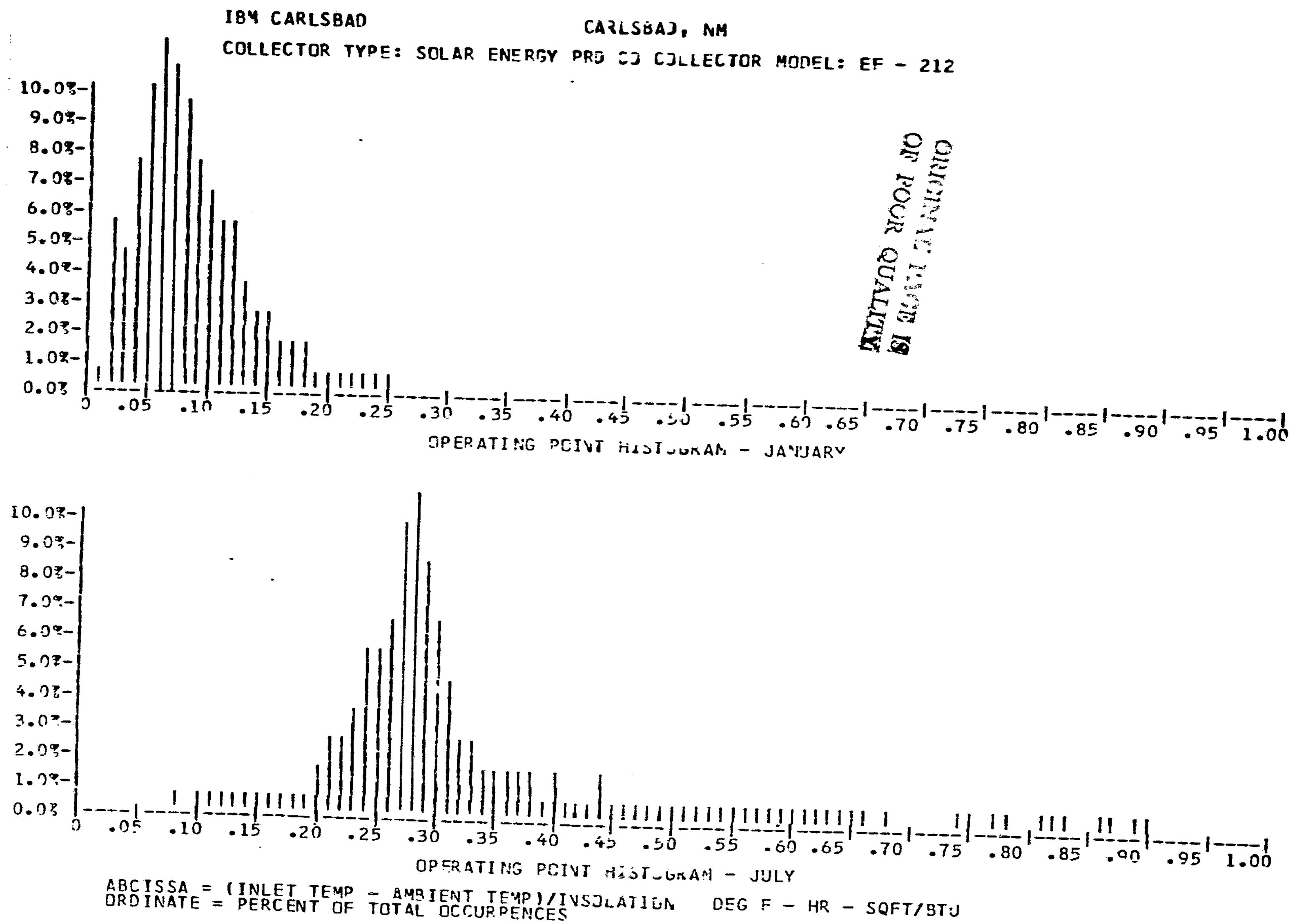

Figure 3.2.1-3 IBM System 1B Operating Point Histogram for Typical Winter and Summer Months

3.2.2 Storage Subsystem

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

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

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 transient system operation and weather conditions can be performed using the parameters listed above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the derivation presented below.

The overall thermal properties of the storage subsystem design can be derived empirically as a function of average storage temperature for the reporting period and the ambient temperature in the vicinity of the storage tank.

An effective storage heat transfer coefficient for the storage subsystem can be defined as follows:

$$C = (Q_{si}-Q_{so}-\Delta Q)/[(T_s - T_a) \times t] \frac{Btu}{Hr-°F} \qquad (9)$$

where

C	=	Effective storage heat transfer coefficient
Q_{si}	=	Energy to storage
Q_{so}	=	Energy from storage
ΔQ	=	Change in stored energy
T_s	=	Storage average temperature
T_a	=	Average ambient tempeature in the vicinity of storage
t	=	Number of hours in the month

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [6]. It has been calculated for each month in this report period and included, along with Storage Average Temperature, in Table 3.2.2-1.

The five month average storage efficiency was 52.9 percent. Rock storage was used only five months from November, 1979, through March, 1980.

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)	Effective Storage Heat Loss Coefficient (Btu/Hr°F)
Nov 79	4.075	2.007	0.049	0.504	108	26
Dec 79	3.352	2.017	0.124	0.639	100	23
Jan 80	3.184	1.592	-0.104	0.467	94	24
Feb 80	1.920	0.658	0.264	0.480	86	17
Mar 80	3.769	2.111	-0.023	0.554	112	20
Total	16.300	3.385	0.310	--	--	--
5-Month Average	3.260	1.677	0.062	0.529	100	22

The storage efficiency values are more closely related to usage than to the design and quality of the storage container. If the energy placed in storage is not used in a short period of time (hours), this energy escapes from storage to the lower temperature surroundings. The rectangular storage enclosure at the IBM System 1B site was located with three walls exposed to outside environment and one wall exposed to inside environment. The bottom of storage was a concrete slab on the ground. Heat loss from storage went to the outside, to the building and to the ground.

The preferred use of storage is illustrated in Figure 2.1-1 (c) where most of the solar energy stored during the day was used that night. Also from Figure 2.1-1 (c) the typical temperature stratification in the rock bed can be seen. With storage near building ambient, the top and bottom of storage may differ by only 5°F. At higher temperatures, 20°F to 40°F differences can exist between the top and bottom of storage.

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 IBM System 1B 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. In System 1B this efficiency is 1.0. The difference between the sum of auxiliary thermal energy plus solar energy and the hot water load is equal to the thermal (standby) losses from the hot water subsystem.

The measured solar fraction in Table 3.2.3-1 is an average weighted value for the month based on the ratio of solar energy in the hot water tank to the total energy in the hot water tank when a demand for hot water exists. This value is dependent on the daily profile of hot water usage. It does not represent the ratio of solar energy supplied to the sum of solar plus auxiliary energy supplied shown in the Table.

For the 12-month period from April, 1979 through March, 1980, the solar energy system supplied a total of 14.686 million Btu to the hot water load. The total hot water load for this period was 21.689 million Btu, and the weighted average monthly solar fraction was 53 percent.

The monthly average hot water load during the reporting period was 1.807 million Btu. This is based on an average daily consumption of 95 gallons, delivered at an average temperature of 141°F and supplied to the system at an average temperature of 67°F. The temperature of the supply water ranged from a low of 54°F in January to a high of 79°F in July.

Each month an average of 1.224 million Btu of solar energy and 0.936 million Btu of auxiliary thermal electrical energy were supplied to the hot water subsystem. Since the average monthly hot water load was 1.807 million Btu, an average of 0.353 million Btu was lost from the hot water tanks each month.

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Energy Supplied (Million Btu)				Hot Water Load (Million Btu)	Average Daily Usage (Gal.)	Hot Water Standby Losses (Million Btu)	Weighted** Solar Fraction (Percent)
	Auxiliary	Auxiliary* Thermal	Solar	Total				
Apr 79	1.032	1.032	1.102	2.34	1.893	99	0.241	49
May 79	0.605	0.605	1.660	2.265	1.701	93	0.564	71
Jun 79	0.506	0.506	1.513	2.019	1.475	88	0.544	71
Jul 79	0.357	0.357	1.308	1.665	1.076	67	0.589	75
Aug 79	0.516	0.516	1.506	2.022	1.551	93	0.471	72
Sep 79	0.907	0.907	0.764	1.671	1.482	91	0.189	39***
Oct 79	0.789	0.789	1.190	1.970	1.667	94	0.312	57
Nov 79	1.001	1.001	1.142	2.143	1.840	93	0.303	50
Dec 79	1.066	1.066	1.091	2.157	1.941	87	0.216	48
Jan 80	1.480	1.480	1.005	2.485	2.338	108	0.147	40
Feb 80	1.561	1.561	1.075	2.636	2.366	116	0.270	39
Mar 80	1.404	1.404	1.330	2.734	2.359	112	0.375	49
Total	11.228	11.228	14.686	25.910	21.689	1141	4.221	--
Average	0.936	0.936	1.224	2.159	1.807	95	0.352	53

*Auxiliary Thermal (the thermal energy applied to the load) is the product of Auxiliary Energy and system efficiency.
**Weighted Solar Fraction is computed at the time hot water is actually used.
***System down most of September.

Hot water usage at the IBM System 1B site averaged 95 gallons per day. the hot water solar fraction varied from 39 percent to 75 percent. The 75 percent solar fraction was for July, 1979 when the system was in the summer mode and usage averaged 67 gallons per day.

Typically only a fair solar day was required for the preheat tank to be charged. Four hours of collector operation would result in 20° to 40°F temperature rise in the preheat tank during the heating season. During the summer mode this same temperature rise could be obtained in two and one half hours due to bypassing storage and allowing the collector air to run hotter.

The two tank DHW subsystem worked well at the Carlsbad site. Hot water usage was good throughout the year so that most of the solar energy put into the preheat tank was used to help meet the hot water load instead of being dissipated in standby losses. It is to be noted that standby losses from the DHW tank must be made up by auxiliary energy in this system. Single tank DHW systems and some configurations of two tank DHW systems permit standby losses to be made up by solar energy, which in most cases would be desirable.

3.2.4 Space Heating Subsystem

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

The performance of the IBM System 1B space heating subsystem is presented in Table 3.2.4-1. For the 5 month period from November, 1979 through March, 1980, the solar energy system supplied a total of 9.659 million Btu to the space heating load. The total heating load for this period was 22.649 million Btu, and the weighted average monthly solar fraction was 43 percent.

The measured space heating subsystem performance was slightly lower than expected during the reporting period. The average inside building temperature for the months of January and February were 74°F and 75°F. Often the temperature was maintained above 75°F. Maintaining these warm temperature during the coldest months increased the contribution to the space heating load by the auxiliary system resulting in a lower space heating solar fraction.

Damper problems reduced space heating performance for February. The system worked well the balance of the heating season supplying a significant percent of the space heating energy.

TABLE 3.2.4-1

SPACE HEATING SUBSYSTEM PERFORMANCE

Month	Space Heating Load (Million Btu)	Energy Supplied (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Nov 79	2.745	2.049	0.695	1.155	75
Dec 79	4.619	2.120	2.499	4.148	46
Jan 80	6.159	1.687	4.472	7.424	27
Feb 80	6.006	1.491	4.515	7.495	25
Mar 80	3.120	2.312	0.808	1.342	74
Total	22.649	9.659	12.989	21.564	
5 Month Average	4.530	1.932	2.598	4.313	43 *

* Average value of Measured Solar Fraction is weighted by the load.

4. OPERATING ENERGY

Operating energy for the IBM System 1B 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 air handler blower power and hot water preheat pump power.

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.

For the April, 1979 through March, 1980 period covered by this report a total of 7.33 million Btu of operating energy was consumed. During the same time a total of 24.35 million Btu of solar energy was supplied to the total system load.

Therefore, for every one million Btu of solar energy delivered to the load, 0.30 million Btu (or 89 kWh) of electrical operating energy was expended.

TABLE 4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Hot Water Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Apr 79	0.467	0.048	0.018	0.534
May 79	0.565	0.062	0.008	0.635
Jun 79	0.512	0.057	0.006	0.575
Jul 79	0.488	0.055	0.000	0.543
Aug 79	0.485	0.054	0.000	0.540
Sep 79	0.256	0.036	0.000	0.292
Oct 79	0.406	0.050	0.000	0.456
Nov 79	0.608	0.051	0.028	0.686
Dec 79	0.689	0.051	0.098	0.838
Jan 80	0.562	0.042	0.171	0.776
Feb 80	0.494	0.046	0.182	0.722
Mar 80	0.645	0.055	0.033	0.733
Total	6.177	0.608	0.544	7.330
Average	0.515	0.051	0.045	0.611

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.

Energy savings for April, 1979 through March, 1980 are presented in Table 5-1. For this time period, the average gross monthly savings were 2.437 million Btu. After the ECSS subsystem operating energy was deducted, the average net monthly electrical savings were 1.923 million Btu. For the overall time period covered by this report the total net savings were 23.072 million Btu.

Based on the energy savings, the system was clearly beneficial throughout the year. Most of the energy savings came during the winter months where both space heating and hot water were required, but the hot water savings were sufficient to justify running the system during the summer months.

TABLE 5-1

ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)	Fossil Energy Savings (Million Btu)	ECSS Operating Energy (Million Btu)	Total Net Savings	
	Hot Water	Space Heating		Electrical (Million Btu)	Fossil (Million Btu)
Apr 79	0.923	0.896	0.467	0.457	0.896
May 79	1.303	0.000	0.565	0.737	0.000
Jun 79	1.192	0.000	0.512	0.679	0.000
Jul 79	0.954	0.000	0.488	0.465	0.000
Aug 79	1.263	0.000	0.485	0.777	0.000
Sep 79	0.642	0.022	0.256	0.391	0.000
Oct 79	0.987	0.251	0.406	0.581	0.251
Nov 79	0.892	3.415	0.608	0.283	3.415
Dec 79	0.895	3.533	0.689	0.204	3.533
Jan 80	0.892	2.812	0.562	0.336	2.812
Feb 80	0.880	2.485	0.494	0.385	2.485
Mar 80	1.157	3.853	0.645	0.510	3.853
Total	11.980	17.267	6.177	5.805	17.267
Average	0.998	1.439	0.515	0.484	1.439

6. MAINTENANCE

This section contains the description of the maintenance performed on the solar system during the 12 month period covered by this report. The motor in the air handler was replaced on September 20, 1979. The damper motor gear box stripped October 20, 1979, and was replaced. The damper motor failed again in February, 1980 and was replaced again. These failures were caused by the lubrication drying out in the high temperature environment. The vendor has been unable to correct the problem in the model of air handler used in this installation. Later versions of the air handler incorporate design changes intended to alleviate this problem, but it is anticipated that the System 1B damper motors will continue to need replacement periodically.

7. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report provides an operational summary of a solar energy system installed at a single family residence at Carlsbad, New Mexico. This analysis was conducted by evaluation of measured system performance and by comparison of measured climatic data with long-term average climatic conditions.

Measured average daily isolation was slightly low for the year, indicating a few more cloudy days than normal. A detail discussion of the insolation data is found in Section 3.1. The yearly average ambient temperature was the same as the long-term average. The weather had negligible adverse impact on the solar system performance.

The space heating and hot water loads were near expected values for the year based on results from modified f-Chart. The system provided solar energy to the building space heat and hot water loads as expected for the year, providing 43 percent of the space heating and 53 percent of the hot water energy. The system showed a good savings by supplying space heating during the five cold months (November through March), and some savings of DHW energy all year.

The system did not meet the total system solar fraction design value of 69 percent. This is attributed to a combination of higher estimated space heating load than was actually encountered and the apportioning of solar energy between the space heating load and the domestic hot water load. Solar energy system losses and high building temperatures also contributed to this deviation.

The air handler dampers and motor were the only hardware failures during the reporting period. The collectors did not show any visible or measureable deterioration during the year. There were no problems with the ducts, rock storage, hot water preheat system or control subsystem.

8. REFERENCES

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

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

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

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

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

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

STORAGE PERFORMANCE

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

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

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

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

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

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

ENERGY COLLECTION AND STORAGE SUBSYSTEM

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

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

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

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

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

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

HOT WATER SUBSYSTEM

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

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

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

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

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

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

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

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

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

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

- HOT WATER USED (HWCSM) is the volume of water used.

SPACE HEATING SUBSYSTEM

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

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

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

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

- <u>ELECTRICAL ENERGY SAVINGS</u> (HSVE) is the cost of the operating energy (HOPE) required to support the solar energy portion of the space heating subsystem.

- <u>BUILDING TEMPERATURE</u> (TB) is the average heated space dry bulb temperature.

- <u>AMBIENT TEMPERATURE</u> (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 a historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

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

- 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

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR IBM SYSTEM 1B

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

These equations are camparable 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 IBM System 1B used for the data evaluation of this report are contained in the following pages and have been included for technical reference and information.

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD(T_2, T_1) \quad \int_{T_1}^{T_2} C_p(T)dt$$

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

SOLAR ENERGY TO STORAGE (BTU)

$$STEI = \Sigma\ [M100 \times HRF\ (T203, T253)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE TO SPACE HEATING (BTU)

$$STEO = \Sigma\ [M400 \times HRF\ (T203, T253)] \times \Delta\tau$$

AVERAGE TEMPERATURE OF STORAGE (°F)

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

TOTAL ENERGY USED BY SPACE HEATING SUBSYSTEM (BTU)

$$HEAT = \Sigma\ [(M400 \times (T400 - T401\ \ + M402 \times (T402 - T401)) \times HRF] \times \Delta\tau$$

TOTAL SOLAR ENERGY USED BY HOT WATER SUBSYSTEM (BTU)

$$HWSE = [M300 * HWD\ (T350, T300)] \times \Delta\tau$$

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

$$CSEO = HEAT + HWSE$$

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

$$CSEO = STEO$$

WHEN SPACE HEATING FROM STORAGE

HEATING AUXILIARY ENERGY

$$HAT = [M402 \times HRF \times (T402 - T401)]$$

$$HAF = 1.66 \times HAT$$

ECSS OPERATING ENERGY (BTU)

$$COPE = 0.5 \times 56.833 \times \Sigma\, EP101 \times \Delta\tau$$

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

$$CSOPE = 56.8833 \times \Sigma\, EP101 \times \Delta\tau$$

WHEN CHARGING STORAGE

SPACE HEATING SUBSYSTEM SOLAR OPERATING ENERGY (BTU)

$$HOPE1 = 0.5 \times 56.8833 \times \Sigma\, EP101 \times \Delta\tau$$

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

$$HOPE1 = 56.8833 \times \Sigma\, EP101 \times \Delta\tau$$

WHEN SPACE HEATING FROM STORAGE

HOT WATER CONSUMED (GALLONS)

$$HWCSM = \Sigma\, WD301 \times \Delta\tau$$

HOT WATER LOAD (BTU)

$$HWL = \Sigma\, [M301 \times HWD(T302, T301)] \times \Delta\tau$$

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

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

HOT WATER OPERATING ENERGY

$$HWOPE = 56.8833 \times \Sigma\, EP301 \times \Delta\tau$$

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HSE = \Sigma\, [M400 * (T400 - T401) * HRF] \times \Delta\tau$$

WHEN SYSTEM USING SOLAR ENERGY FOR HEATING

AUXILIARY ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HAT = \Sigma\, [M402 * (T402 - T401) * HRF] \times \Delta\tau$$

WHEN SYSTEM USING AUXILIARY ENERGY FOR HEATING

$$HOPE2 = 56.883 \times \Sigma\, EP402 \times \Delta\tau$$

SPACE HEATING ELECTRICAL ENERGY SAVINGS

$$HSVE = -HOPE1$$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

HOPE = HOPE1 + HOPE2

SUPPLY WATER TEMPERATURE (°F)

TSW = T301

HOT WATER TEMPERATURE (°F)

THW = T302

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)

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 = HSE + HWSE

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

AUXILIARY THERMAL ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWAT = HWAE

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = 100 x HWTKSE/(HWTKSE + HWTKAUX)

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

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

HWSVE = HWSE1 - HWOPE

SPACE HEATING LOAD (BTU)

HL = HAT + HSE

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

HSFR = HOPE1

SPACE HEATING SUBSYSTEM FOSSIL SAVINGS (BTU)

HSVF = HSE/FEFF

WHERE FEFF IS THE FURNACE THERMAL EFFICIENCY

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 = HOPE + HWOP + CSOPE

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HWAE + HAE

AUXILIARY FOSSIL ENERGY TO LOADS (BTU)

AXF = HAF

TOTAL FOSSIL ENERGY SAVINGS

TSVF = HSVF

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HWSVE + HSVE - CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXE + SECA + AXF

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/[AXF + 3.33 x (AXE + SYSOPE)]

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

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

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

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

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

SITE: IBM CARLSBAD 86. LOCATION: CRLSBD CVRNS NM

ANALYST: M. STRICKLAND FORIVE NO.: 52.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: -26.00 (DEGREES)

LATTITUDE: 33.00 (DEGREES) RUN DATE: 4/11/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1699.	1091.	0.64252	1.590	1735.	734	0	41.
FEB	2123.	1423.	0.66875	1.370	1950.	533	0	46.
MAR	2654.	1862.	0.70163	1.157	2154.	400	0	52.
APR	3162.	2271.	0.71819	0.966	2194.	151	49	62.
MAY	3490.	2511.	0.71950	0.837	2102.	0	155	71.
JUN	3611.	2625.	0.72694	0.781	2051.	0	413	79.
JUL	3542.	2426.	0.68486	0.809	1963.	0	496	81.
AUG	3230.	2249.	0.68559	0.908	2042.	0	455	80.
SEP	2332.	1921.	0.67839	1.071	2057.	7	245	73.
OCT	2278.	1574.	0.69117	1.300	2047.	132	59	63.
NOV	1797.	1195.	0.66498	1.538	1836.	440	1	50.
DEC	1576.	1003.	0.63621	1.664	1669.	592	0	43.

LEGEND:

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

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

KBAR ==> RATIO OF HBAR TO HOBAR.

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

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

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

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

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

REFERENCES

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

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

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

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

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