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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR DECADE 80 HOUSE, TUCSON, ARIZONA

Prepared by

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National Aeronautics and Space Administration
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16. ABSTRACT

This report has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. It is one of a series of reports describing the operational and thermal performance of a variety of solar systems installed in Operational Test Sites under this program. The analysis used is based on instrumented system data monitored and collected for at least one full season of operation. The objective of the analysis is to report the long-term field performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The Solar Energy System was designed by Copper Development Association, Inc., New York, New York, to provide domestic hot water and a 3,200 square foot floor area with space heating and space cooling to a one-story, single family residence located in Tuscon, Arizona. The Solar Energy System consists of a 1,923 square foot flat plate collector array subsystem, a 3,000 gallon tank storage subsystem, pumps, controls and heat transfer medium lines. A Propylene Glycol (30 percent) and water (70 percent) solution is used as the energy collection and heat transfer medium. The collector-to-storage loop also contains a heat exchanger used to heat a swimming pool. The domestic hot water subsystem consists of a 66 gallon conventional electric storage tank to which solar energy is supplied by a pump circulating water through a heat exchanger immersed in the 3,000 gallon storage tank. Auxiliary energy for heating is provided by a gas-fired 150,000 Btu/hour boiler. Space cooling is provided by two absorption cycle water chillers operating in parallel. The Solar Energy System has four modes of operation.

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1. FOREWORD

The Solar Energy System Performance Evaluation - Seasonal Report has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. The analysis contained in this document describes the technical performance of an Operational Test Site (OTS) functioning throughout a specified period of time which is typically one season. The objective of the analysis is to report the long-term performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The contents of this document have been divided into the following topics of discussion:

- System Description
- Performance Assessment
- Operating Energy
- Energy Savings
- Maintenance
- Summary and Conclusions

Data used for the seasonal analyses of the Operational Test Site described in this document have been collected, processed and maintained under the OTS Development Program and have provided the major inputs used to perform the long-term technical assessment.

The Seasonal Report document for Decade 80 House culminates the technical activities for the site. The fact that the site was constructed as a show place makes its costs unique. Consequently, no economic analysis such as is performed for other OTS sites in a final report is feasible. Other documents specifically related to this system are References [1], [2].*

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*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The Decade 80 House solar energy system is designed to provide domestic hot water, space heating and space cooling to a one story, single family residence located in Tucson, Arizona. The dwelling contains 3200 square feet of conditioned living space.

The collector subsystem consists of a 1923 square feet flat plate collector array which has been integrated into the roof of the dwelling. The array faces due south and is tilted at an angle of 26.5 degrees from the horizontal. A solution of propylene glycol and water (30 percent propylene glycol by volume) is used as the energy collection and transfer medium. Collected solar energy is transferred to water contained in a buried, 3,000 gallon tank. The collector-to-storage loop also contains a heat exchanger used to heat a swimming pool.

The domestic hot water subsystem consists of a 66-gallon storage tank to which solar energy is supplied by a pump circulating water through a heat exchanger immersed in the larger 3,000 gallon storage tank. Auxiliary energy is provided to this subsystem by conventional electric heating elements in the 66 gallon domestic hot water tank. Hot water is continuously circulated from the hot water tank throughout the building plumbing so that hot water is immediately available on demand.

The heating subsystem consists of a pump for withdrawing hot water from the storage tank and circulating it through heat exchangers located in the air distribution system of the dwelling. Auxiliary energy for heating is provided by a gas fired, 150,000 Btu/hour boiler which can be used either to add heat to the water from the hot storage tank or to heat water circulating between the load heat exchangers and the boiler only.

Space cooling is provided by two absorption cycle water chillers operating in parallel in a primary/secondary configuration. Energy stored in the hot solar storage tank is circulated through the generators of these chillers to activate the absorption cycle. Chilled water produced in this manner is pumped to the heat exchangers located in the air distribution system of the building. Whenever solar energy is insufficient to activate the refrigerant cycle, auxiliary energy is provided by the gas fired boiler.

The system is shown schematically in Figure 2-1. The residence with the collectors integrated into the roof is shown in Figure 2-2. The system has four modes of operation:

Mode 1 - Collector-to-Storage: The collector pump (pump P1) is actuated when the collector absorber plate surface temperature is 8°F hotter than the water in the middle of the hot storage tank. This pump then circulates the propylene glycol solution through the collector to the heat exchanger where the collected energy is transferred to water circulating from the hot storage tank by pump P2. Pump P2 is activated when the fluid temperature out of the collector is 5°F hotter than that of the water in the middle of the hot storage tank. When the temperature of the water in the bottom of the hot storage tank rises to within 2°F of that of the collector absorber plate surface, this mode is terminated.

Mode 2 - Domestic Hot Water Heating: When the temperature of the water in the domestic hot water tank falls below the internal thermostat setting (normally set at 135°F), water is withdrawn and circulated through the heat exchanger immersed in the 3,000 gallon storage tank provided that the temperature in the upper portion of this tank is 5°F higher than the thermostat setting. If this condition is not met, the auxiliary immersion heaters provide the required energy. As hot water is used, make-up water from the utility main is passed through the heat exchanger in the 3,000 gallon hot storage tank prior to being admitted into the domestic hot water tank.

Mode 3 - Storage-to-Space Heating: Space heating is controlled by a two-stage thermostat, with the stages set 1-1/2°F apart. When the first stage of this thermostat calls for heat, hot water is drawn directly from the hot storage tank and pumped to the heat exchangers in the air circulation duct. If sufficient heat energy is not available and the second stage is then activated, water is circulated through the boiler, where auxiliary energy is added, bypassing the hot storage tank.

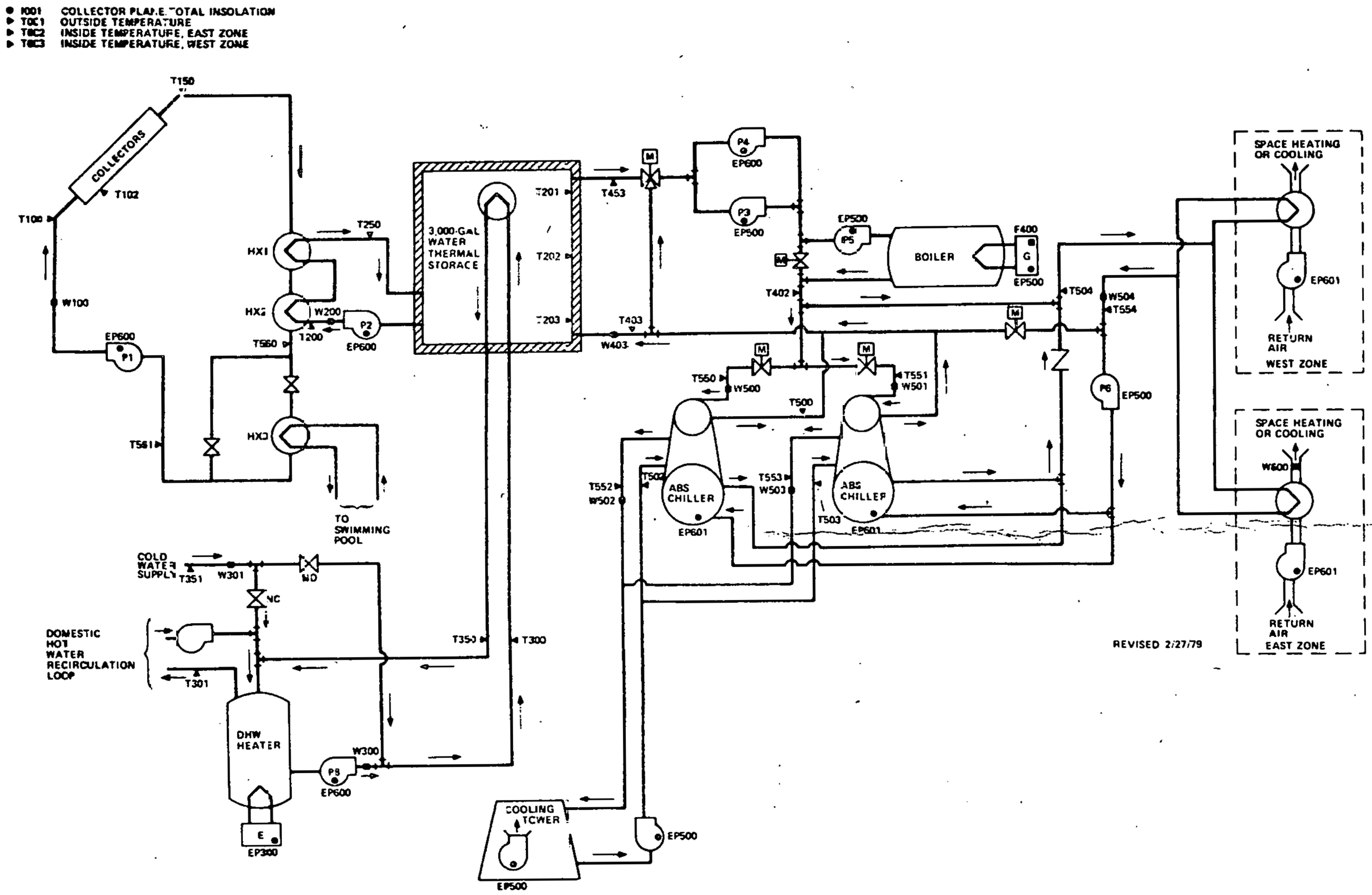

Figure 2-1. DECADE 80 HOUSE SOLAR ENERGY SYSTEM SCHEMATIC

Figure 2-2 DECADE 80 HOUSE PICTORIAL

Mode 4 - Space Cooling: The space cooling controls also include a two-stage thermostat. The first stage is manually set to the desired room temperature, while the second stage is always at a setting 1-1/2°F higher than that of the first. When the cooling system is turned on by a demand from the first stage, the primary chiller is activated. Hot water is drawn from the storage tank to the generator of this chiller - provided that the temperature of the water is at or above 180°F. The chilled water produced is circulated through the heat exchangers in the air circulation system to cool the dwelling. If, after 7 minutes, the temperature of the building is not at or below the setting of the second stage, the secondary absorption chiller is activated and continues to operate in parallel with the primary unit until the setting on the second stage is reached. At this time, the secondary unit shuts down and the primary unit continues to operate until the desired room temperature (the setting for the first thermostat stage) is reached. If the water provided to the generator(s) is less than 180°F, the auxiliary boiler is activated to provide the necessary energy directly to the chillers. If the temperature of the water returning from the generator(s) is less than that of the water at the top of the hot storage tank, the returning water is circulated through the hot storage tank on its way to the boiler; otherwise the hot storage tank is bypassed.

The sensor designations shown in Figure 2-1 are in accordance with NBSIR-76-1137 [4]. The measurement symbol prefixes: W, T, EP, I and F represent respectively: flowrate, temperature, electric power, insolation and fossil fuel rate.

2.1 Typical System Operation

Operation of the Decade 80 House solar energy system has taken place in essentially two seasons: heating and cooling. Curves depicting the system operation on two days, one typical of space heating, the second typical of space cooling, are presented in Figure 2.1-1 through 2.1-7. In both instances the total and operationally incident insolation are shown along with representative thermal storage parameters. A composite plot showing chiller array COP vs. generator inlet temperature is presented for the day requring space cooling. This day, July 28, was chosen since the primary chiller was the only unit in operation.

As shown in Figure 2.1-2, the collector pump P1 came on just prior to 10:00 AM and shut off at 5:00 PM. Storage temperature was raised from a nominal 63°F to a high of 181°F, as seen in Figure 2.1-3, despite nearly constant usage by the chiller array. Figure 2.1-4 shows the chiller operation as a function of generator inlet temperature. The average COP for the day was 0.52. On this typical day the system operated in a manner which was consistent with design criteria. There were 3.9 million Btu of incident energy of which 1.0 million Btu were collected and 0.99 million Btu put into the storage medium. This represents a collector array efficiency of 26 percent. From storage, 0.9 million Btu were removed for use by hot water and space cooling loads, for a solar conversion efficiency of 23 percent.

Figure 2.1-5 shows the total and operationally available insolation for a typical day in the heating season. From Figure 2.1-6 it can be seen that the collector pump turned on at 8:45 AM and ran until 4:45 PM. The storage pump did not come on until 10:15 AM, however, and turned off at 3:45 PM. A total of 3.9 million Btu were available for collection and the system collected 1.6 million Btu for a collector array efficiency of 41 percent. This unsually high efficiency may be largely due to the affects of pool heating which began on this day. The pool heating also accounts for the relatively small rise in temperature of the storage volume. Even though a large amount of energy was collected only 42 percent of the heating load was provided by solar energy, the majority being diverted for pool heating.

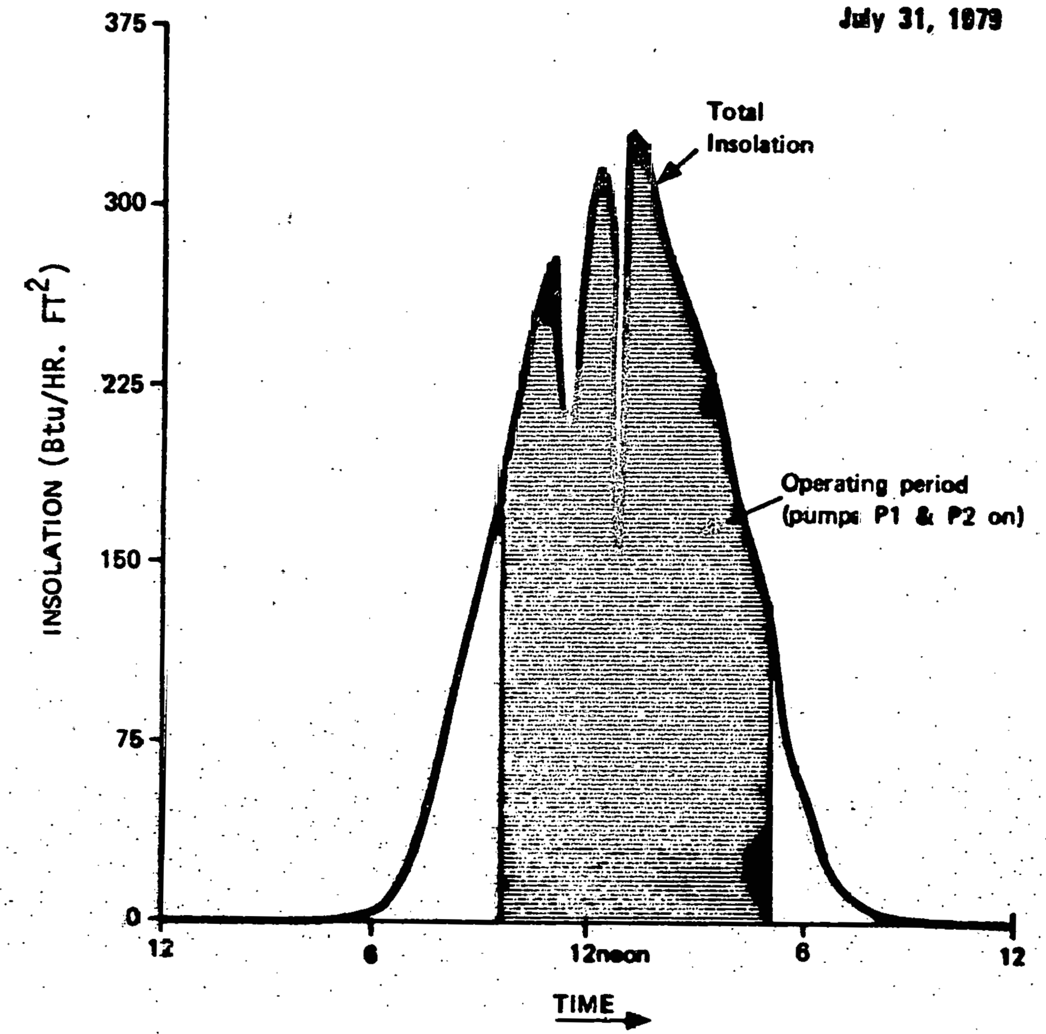

Figure 2.1-1 TOTAL INSOLATION AND OPERATIONAL INSOLATION JULY 31, 1979

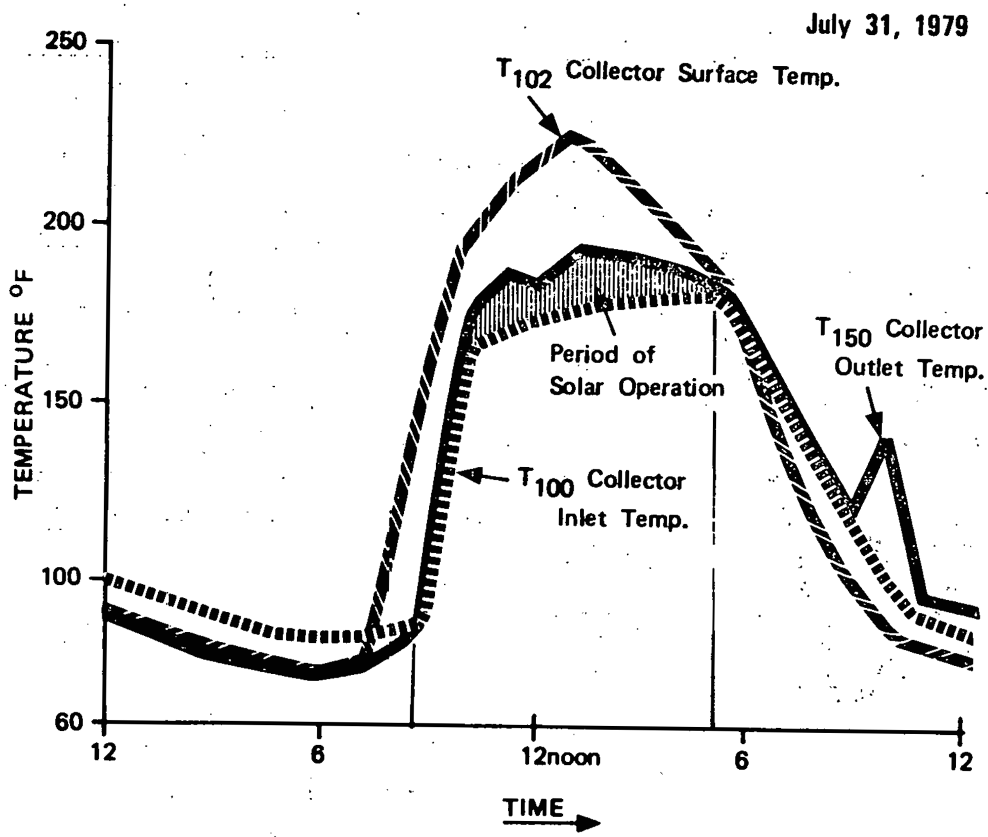

Figure 2.1-2 COLLECTOR LOOP OPERATION JULY 31, 1979

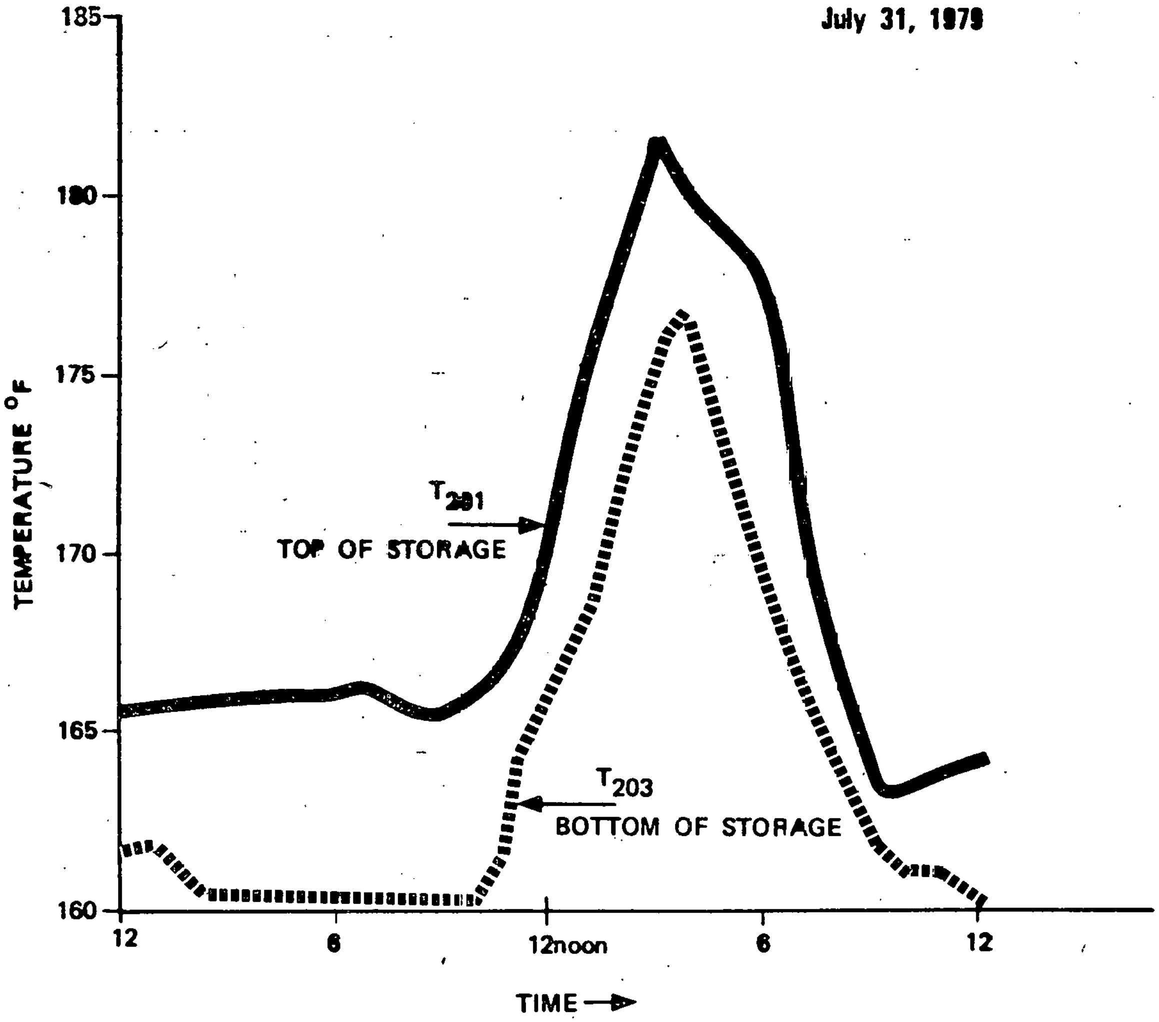

Figure 2.1-3 STORAGE PROFILE JULY 31, 1979

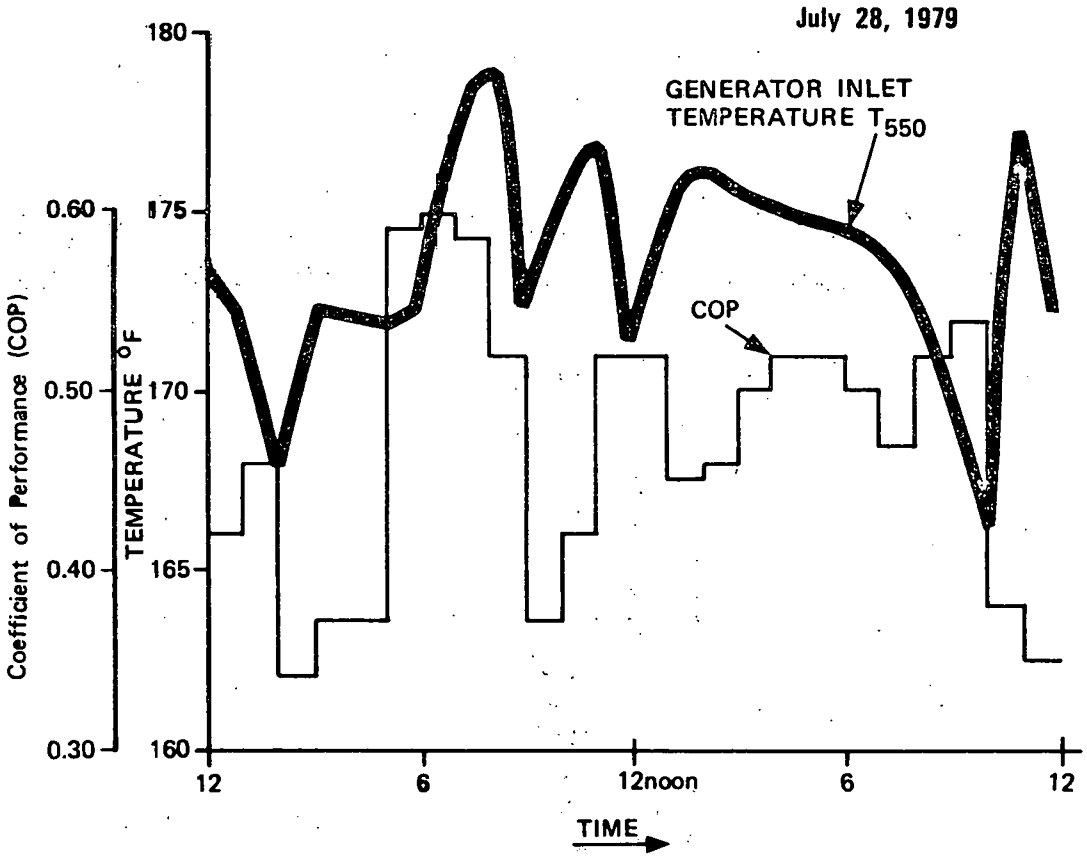

Figure 2.1-4 COOLING SYSTEM FOR TYPICAL DAY WITH PRIMARY CHILLER OPERATION

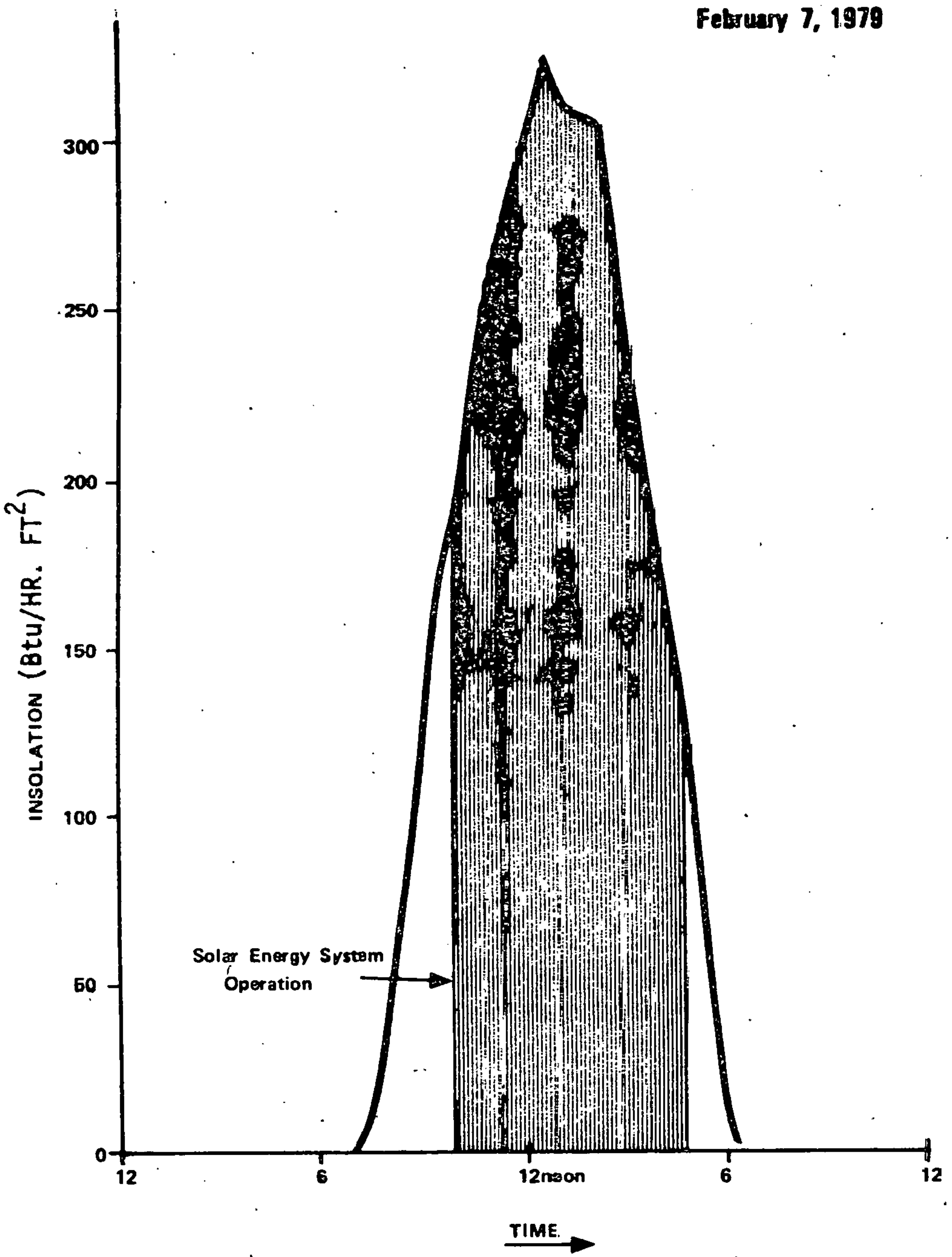

Figure 2.1-5 TOTAL INSOLATION AND OPERATIONAL INSOLATION FEBRUARY 7, 1979

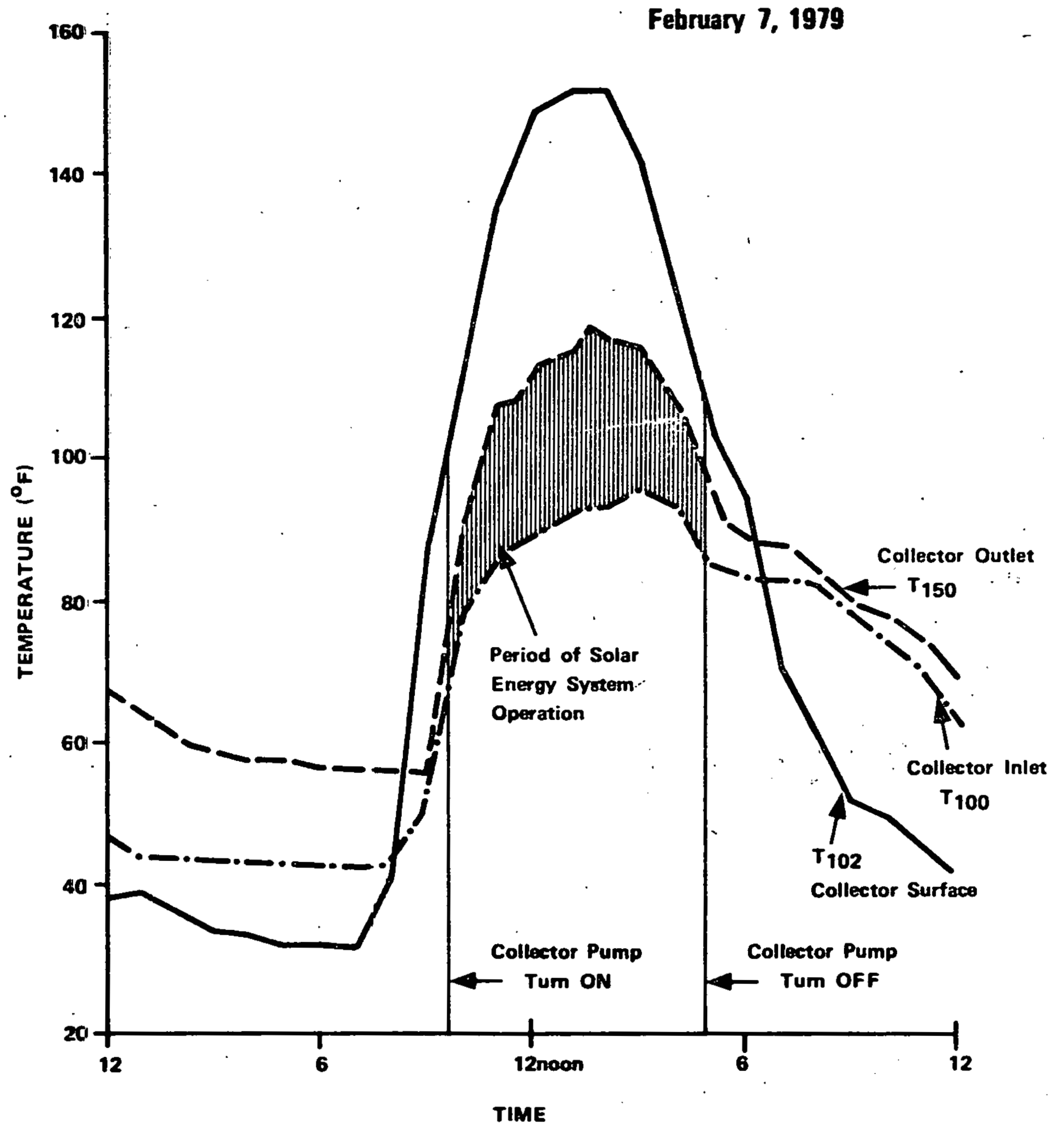

Figure 2.1-6 COLLECTOR LOOP OPERATION FEBRUARY 7, 1979

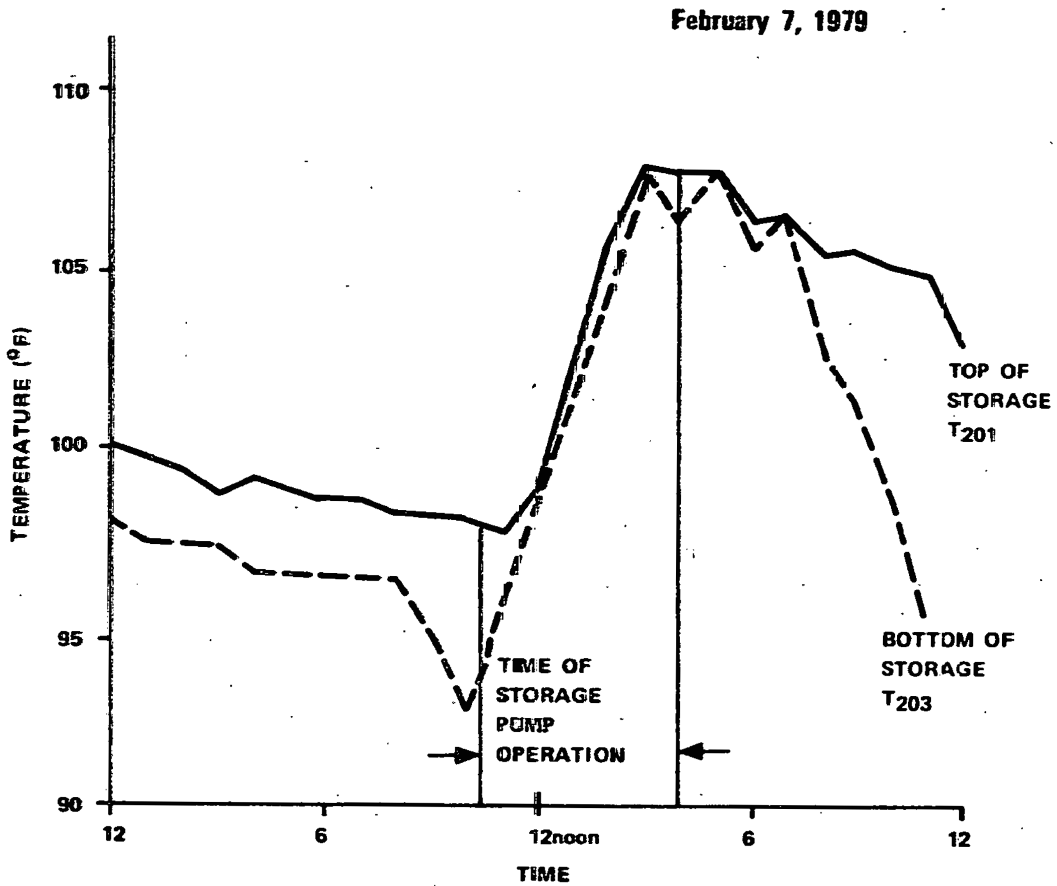

Figure 2.1-7 STORAGE PROFILE FEBRUARY 7, 1979

2.2 System Operating Sequence

For July 28 and February 7, 1979, the days selected to represent the typical system operation, the sequences are shown in Figure 2.2-1 and 2.2-2. Throughout most of the cooling season the house was unoccupied and there was no consumption of hot water. All other subsystems remained operative in their normal modes. On the typical cooling day, collection of energy began at 9:45 AM and ceased at 4:50 PM. From the total 3.9 million Btu available, the solar energy system was able to collect 1.0 million Btu during this time. Cooling was required throughout the day except for a brief interval about 6:00 AM. Both chillers were in operation most of this time with the secondary chiller operating approximately three hours less than the primary. Assistance from the auxiliary gas supply was required until 11:00 AM because the temperature of storage could not be raised to suitable levels. Solar energy was depleted and auxiliary was again required beginning at 10:00 PM. The cooling load was 0.95 million Btu. Slightly more than 1.0 million Btu of solar energy and 1.4 million Btu of auxiliary energy was required to produce this cooling effect. The average ambient temperature was 84°F and the house was maintained at 80°F.

Typical operation during the heating season is illustrated by data from February 7, 1979, shown in Figure 2.2-1. The collector array was in operation between 9:30 AM and 4:45 PM, collecting approximately 1.6 million Btu. Maintaining the inside temperature at an average 70°F in the presence of a 46°F ambient resulted in a space heating load of 0.8 million Btu. Relatively heavy use of the space heating subsystem early in the month depleted the storage of solar energy. This was reflected by the heavy use of auxiliary to supply the space heating requirement. This was also the first day of pool heat exchanger operation and a significant amount of collected energy was diverted for this purpose. After the collection system began operation, however, the need for auxiliary diminished dramatically. The frequent cycling of the space heating subsystem appeared to be the normal mode for the Decade 80 House, however, this is not normally desirable. The cause may be related to an improper thermostat anticipator setting or to high infiltration rates.

The consumption of hot water occurred primarily during the hours between 8:00 and 11:00 AM when 117 gallons were used. There was little immediate contribution from the solar energy system since the temperature of storage was below the threshold (145°F) required before the preheating operation is initiated. Auxiliary energy was used to meet all stand-by losses and to resupply the tank following the heavy usage.

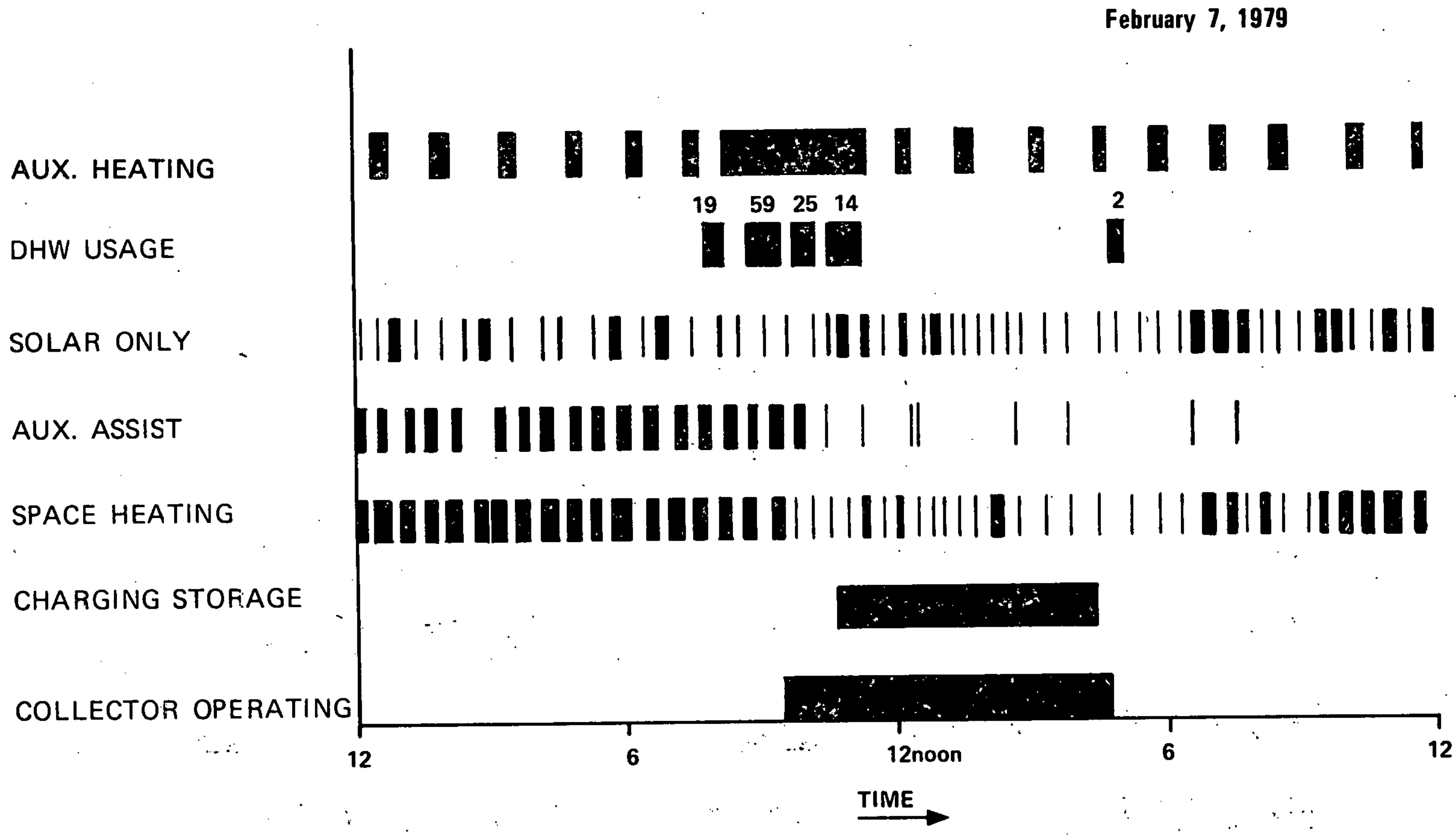

Figure 2.2-1 TYPICAL SYSTEM OPERATING SEQUENCE HEATING SYSTEM

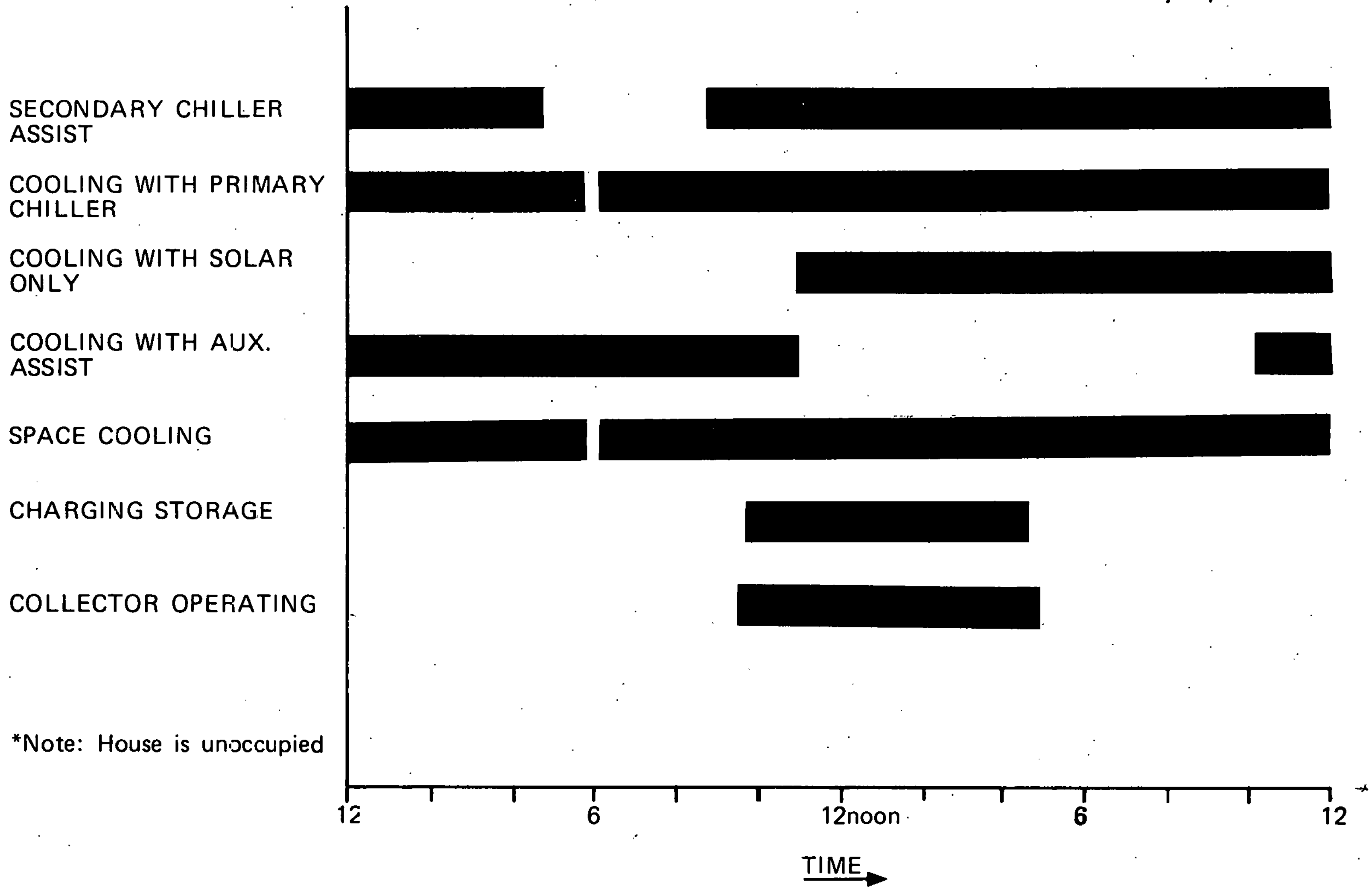

Figure 2.2-2 TYPICAL SYSTEM OPERATING SEQUENCE COOLING SYSTEM

3. PERFORMANCE ASSESSMENT

The performance of the Decade 80 House Solar Energy System has been evaluated for the November 1978 through September 1979 time period from two perspectives. The first was the overall system view in which the performance values of system solar fraction and net energy savings were evaluated against the prevailing and long-term average climatic conditions and system loads. The second view presents a more in depth look at the performance of the individual subsystems. Details related to the performance of the system are presented first in Section 3.1 followed by the subsystem assessment in Section 3.2.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the Decade 80 House Solar Energy System located in Tucson, Arizona. 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 are evaluated in subsequent sections of this report.

The measurement data were collected for the period November 1978 through September 1979. System performance data were provided through an IBM developed Central Data Processing System (CDPS) [3] consisting of a remote Site Data Acquisition System (SDAS), telephone data transmission lines and couplers, an IBM System 7 computer for data management, and an IBM system 370/145 computer for data processing. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. These data are processed daily and summarized into monthly performance assessments which then provide a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data contained in this report.

The solar energy system performance summarized in this section can be viewed as the dependent response of the system to certain primary inputs. This relationship is illustrated in Figure 3.1-1. The primary inputs are the incident solar energy, auxiliary thermal 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. The input and output definitions follow:

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.

- Auxiliary Thermal Energy - Energy derived from an auxiliary source (natural gas) used to supply the thermal needs of the various subsystems.

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

Outputs

- System Solar Fraction - The ratio of solar energy applied to the system loads to total energy requirement of the system.

- 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 the System Performance Summary Table 3.1-1. Comparative long-term average values of daily incident solar energy, and outdoor ambient temperature are given for reference purpose. The long-term data are taken from Reference 1 of Appendix C. Generally the solar energy system is designed to supply an amount of energy that results in a desired value of system solar fraction while operating under climatic conditions that are defined by the long-term average value of daily incident

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY
DECADE 80 HOUSE

Month	Daily Incident Solar Energy per Unit Area @26.5° 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	
Nov 78	1276 (1)	1742	54	54	9.927	99	100	16.426
Dec 78	1369	1510	49	52	16.379	85	76	21.186
Jan 79	1184	1613	47	51	19.197	80	60	22.276
Feb 79	1825	1892	54	54	33.418 (4)	78	66	15.542
Mar 79	1784	2173	57	58	22.664 (4)	94	80	14.704
Apr 79	2333	2425	65	66	17.944 (4)	100/14 (3)	100/35 (3)	8.704
May 79	1985	2476	69	74	7.741	70	100	26.848
Jun 79	1965	2414	77	82	15.860	46	90	27.819
Jul 79	2041	2127	81	86	21.775	49	80	31.741
Aug 79	1972	2133	76	84	14.007	56 (2)	25	4.737
Sep 79	2107	2189	78	80	14.894	50 (2)	50	11.982
Total	--	--	--	--	178.912	--	--	201.965
Average	1804	2063	64	68	16.264	69 (5)	72 (5)	18.360

NOTES:

1. Site reactivated with new instrumentation Nov. 11. Only 20 days data available.
2. Task problems caused estimation to be used.
3. Heating and Cooling required, solar fractions given in that order.
4. Swimming pool heating included with normal heating and cooling loads.
5. Figure includes a composite solar fraction for transition month.

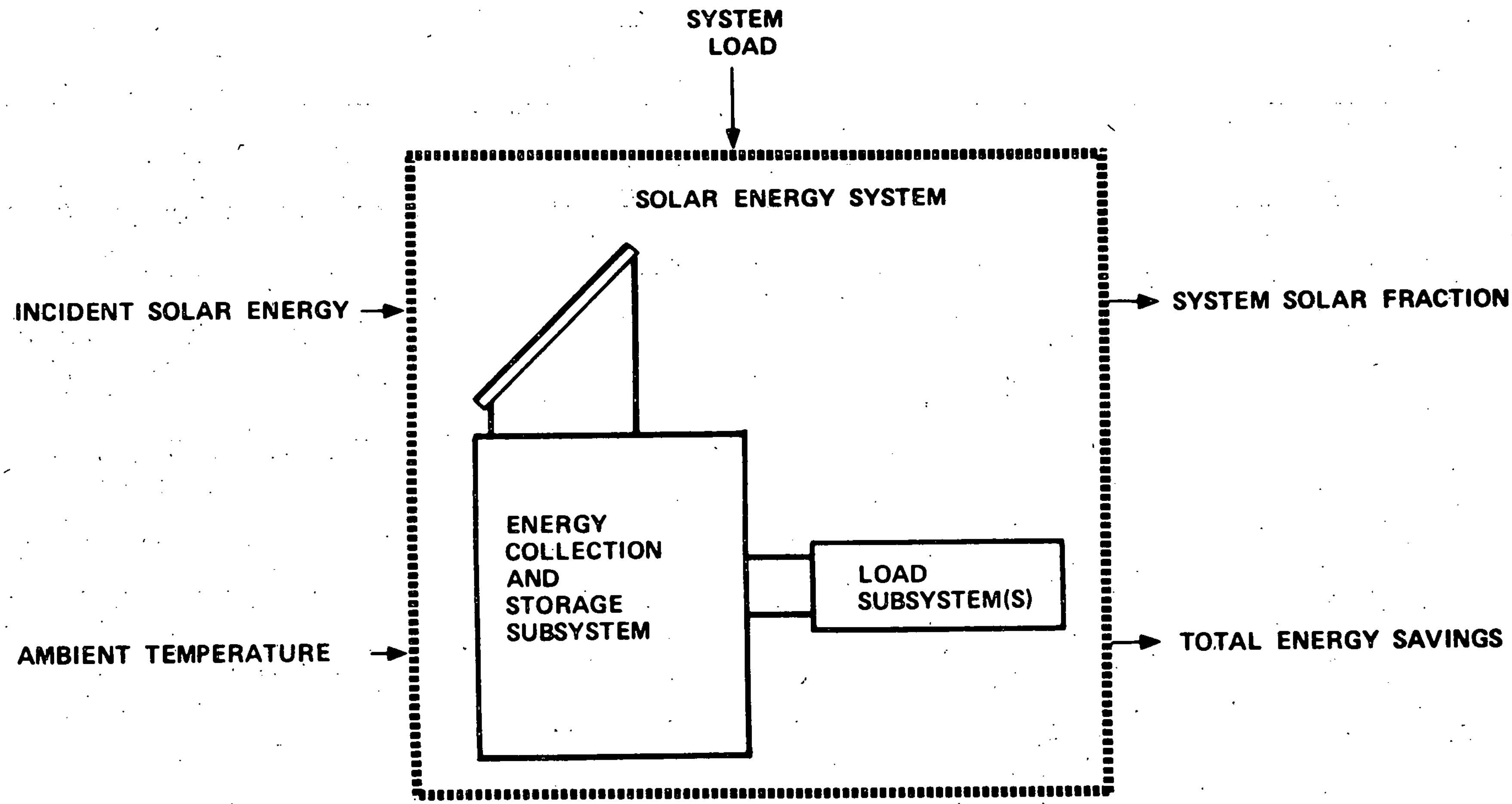

Figure 3.1-1 Solar Energy System Evaluation Block Diagram

solar energy and outdoor ambient temperature. If the actual climatic conditions are close to the long-term average values, there is little adverse impact on the system's ability to meet design goals. This is an important factor in evaluating system performance and is the reason the long-term average values are given. The data reported in the following paragraphs are taken from Tables 3.1-1, 3.1-2 and 3.1-3.

In order to evaluate system performance, some reference or comparative standard must first be established as a basis for comparison. Included in Tables 3.1-2 and 3.1-3 are expected values for subsystem solar fractions. These expected values have been derived from two sources: the modified f-Chart [9] approach for hot water and space heating and a method described in the following paragraph for space cooling. The modified f-Chart approach is based upon the method developed at the University of Wisconsin [8]. The inputs for the collector array data are based upon measurements taken at the site which are processed to establish Hottel-Whiller-Bliss model by a technique developed by McCumber [7]. This was done because the collectors were not purchased as entities, but were built and installed in the the house at the time of construction. The model used in the analysis is based on manufacturers' data and other known system parameters. The bases 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-Chart; 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 is 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 intalled at the stie.

The following estimation method for space cooling loads was used. This method is basically the standard ASHRAE technique used to size conventional air conditioning equipment. The long-term average cooling degree days are multiplied by the average UA of the building. A constant 30 percent is then added to account for latent loads. This technique is implemented as follows:

$$CL_{est} = UA \times LATENT \times CDD_i \times 24$$

where UA = 1000 Btu/°F. hr. obtained from builder's test data and empirically from data obtained through the data network

LATENT = 1.3 (ASHRAE estimate)

CDD_i = long-term average cooling degree days in i^{th} month

Table 3.1.3 shows the comparison of the measured data with the assumed method for calculating cooling load.

The performance will be discussed in two segments: heating was required from November 1978 through April 1979; cooling was necessary for April through September 1979. April represents a transition month. Domestic hot water was used to some extent throughout the entire period, although, during months without occupants, the load was sporadic, being drawn mainly to test the state of readiness of the system. Both the space cooling and heating subsystems remained active under thermostatic control despite the lack of occupants, thus loads were recorded without the usual perturbations caused by normal occupancy.

Table 3.1-2 shows that the expected space heating load based on long-term average heating degree day data is smaller than the actual load encountered at the site since the temperatures were on the order of 3°F to 4°F lower on the average than the norms. Although available solar energy was approximately 11 percent lower than average there was still sufficient energy available for collection and direct gain did not play as large a role in heating the house. Because of this the solar space heating subsystem was exercised to a greater extent and was able to satisfy a higher percentage of the load. The lower-than-average ambient temperature improved collection efficiency by reducing the loss factor, thus improving the efficiency/operating point balance.

TABLE 3.1-2

ACTUAL AND PREDICTED HEATING SYSTEM PERFORMANCE

Month	Heating Load Meas. ($X10^6$ Btu)	Heating Load Predict. ($X10^6$ Btu)	Solar Fraction Meas.	Solar Fraction Expect.	Solar Energy Used ($X10^6$ Btu)	Auxiliary Energy Used ($X10^6$ Btu)	Outside Temperature (°F) Meas.	Outside Temperature (°F) Long Term
Nov	9.77	8.75	100	100	9.77	0	54	59
Dec	16.05	13.95	86	76	13.88	2.17	49	52
Jan	18.75	13.13	80	60	14.95	2.63	47	51
Feb	10.80	6.36	93	66	10.08	0.76	54	54
Mar	9.02	2.18	98	95	8.84	0.21	57	58
Apr	3.15	1.78	100	100	3.15	0	65	66
Total	67.54	46.15	--	--	60.67	5.77	--	--
Average	11.26	7.69	92.8	82.8	10.11	0.96	47	48

Table 3.1-3 shows that under the assumption used to generate the expected cooling loads, the loads encountered at the site during the report period agreed quite well. However, the absorption chiller total coefficent of performance (COP) was significantly lower than would ordinarily be expected based solely on the measured generator inlet temperatures. This leads to the conclusion that, had the total chiller COP been as high as anticipated, the cooling subsystem solar fraction would have been much higher. There are at least two possible explanations for this lower COP. It is known that chiller maintenance was performed in August, and, as may be seen by Table 3.1-3, a significant improvement in COP was observed after that visit. At this time it was also learned that excess auxiliary thermal energy had been expended to heat generator inlet water to temperatures often greater than 190°F. This had the adverse effects of wasting auxiliary energy (reducing the solar fraction) and over-firing the absorption chillers thereby lowering their efficiency.

The operation of the two chillers in a primary/secondary mode, with the secondary chiller cycling on and off, may also have contributed to the lower COP (resulting in the lower solar fraction). It is characteristic of chillers to require a warm-up period during which they do not operate efficiently. Perhaps the more constant operation of the two with the addition of some cold thermal storage would have served to improve both total COP and solar fraction.

In either event it can be seen that the capacity of the cooling subsystem is adequate to meet the nominal cooling requirements of the house. System solar fraction might have been significantly better had the chiller array functioned properly.

Net energy savings were realized during every month of the reporting period. These total savings are reported in Table 3.1-1 and are broken down by subsystem and energy type in Table 5-1.

TABLE 3.1-3

ACTUAL AND PREDICTED COOLING SYSTEM PERFORMANCE

Month	Average Temperature Meas. (°F)	Average Temperature Long Term	Cooling Degree Days Meas.	Cooling Degree Days Long Term	COP(2) Meas.	Storage Temp. (°F)	COP Expected	Cooling Load(3) Meas. ($X10^6$ Btu)	Cooling Load(3) Long Term	Solar Frac. Meas.	Solar Frac. Exp.	Solar Used ($X10^6$ Btu)
Apr	65	66	87	96	0.31 (1)	171	0.61	3.54	2.99	14	35	1.702
May	69	74	168	272	0.57	176	0.69	7.51	8.49	73	100	17.934
Jun	77	82	368	513	0.32	174	0.67	15.86	16.00	47	90	21.366
Jul	81	86	500	660	0.39	173	0.66	21.77	20.59	49	80	24.879
Aug	76	84	331	583	0.57 (1)	176	0.69	13.56	18.19	56	25	6.505
Sep	78	80	385	453	0.58 (1)	177	0.71	13.67	14.73	50	50	10.906
Total	--	--	1839	2577	--	--		75.91	80.99	--	--	83.292
Average	74.3	78.7	306.5	429.5	0.46	174.5	0.67	12.65	13.50	48.2	63.3	13.883

NOTES:

(1) Estimations used to circumvent instrumentation anomalies
(2) COP is for entire array, not individual chillers
(3) Cooling Load (Long-Term) = UA X LATENT X DD_i X 24

where UA = $1000 \frac{Btu}{hr°F}$ dwelling thermal constant

LATENT = 1.3 (ASHRAE estimate for latent cooling load)

DD_i = Cooling degree days for i^{th} month

3.2 Subsystem Performance

The Decade 80 House solar energy installation may be divided into five subsystems:

1. Collector Array
2. Storage
3. Hot Water
4. Space Heating
5. Space Cooling

Each subsystem has been evaluated by the techniques defined in Section 3 and is numerically analyzed each month for the monthly performance summaries. This section presents the results of integrating the monthly data available on the five subsystems for the period November 1978 through September 1979.

3.2.1 Collector Array Subsystem

The Decade 80 House collector array consists of Revere, laminated panel, integrated roof/flat plate liquid collectors having a gross area of 1923 square feet and interconnected with parallel supply and return feeders. The absorber surface has been painted with 3M "Black Velvet" and a double glazing of PPG "Twindow" was used. The flow path through each collector panel is serpentine. Interconnection and flow details, as well as other pertinent operational characteristics, are shown in Figure 3.2.1-1 (a) and (b). The collector subsystem analysis and data are given in the following paragraphs.

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

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

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.

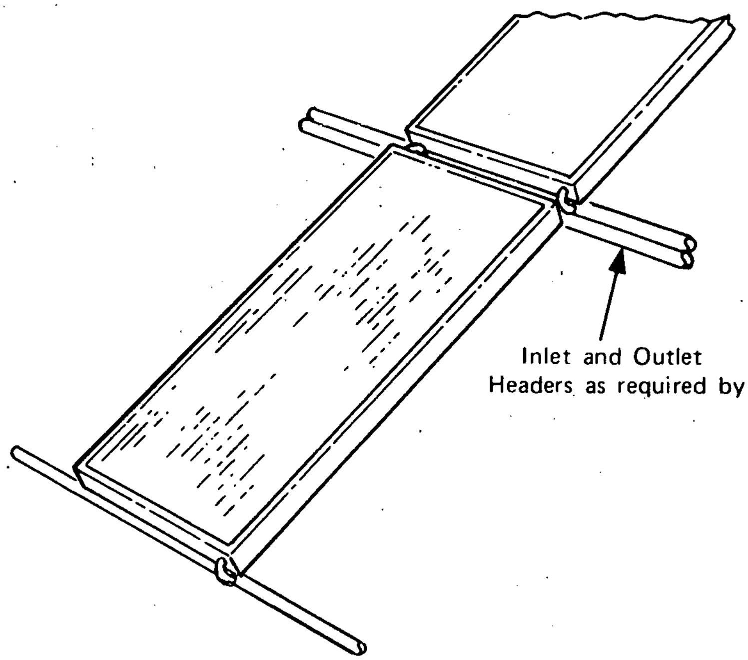

Figure 3.2.1-1(a) COLLECTOR ARRAY ARRANGEMENT (2 SINGLE PANELS)

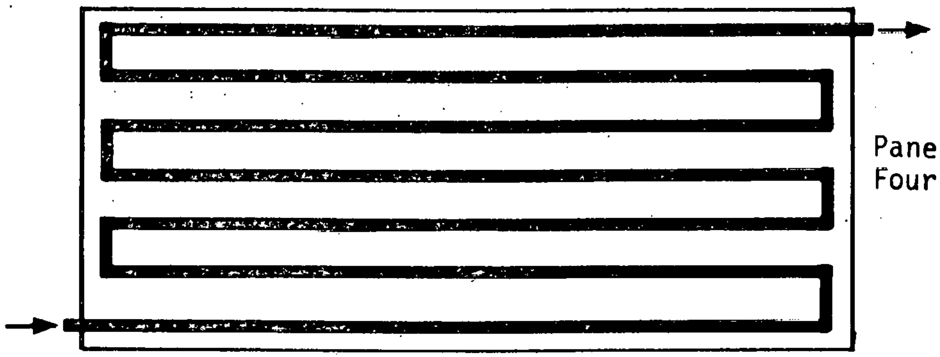

Figure 3.2.1-1(b) COLLECTOR PANEL LIQUID FLOW PATH (SERPENTINE)

Collector Data

Manufacturer - Revere

Model - Special, built in place

Type - Liquid

Number of Collectors - integral with roof

Flow Paths - One

Site Data

Location - Decade 80 House
Tucon, Arizona

Latitude - 32.7°N

Collector Tilt - 26.5°

Longitude - 111°W

Azimuth - 0°

Figure 3.2.1-1 COLLECTOR ARRAY SCHEMATIC

TABLE 3.2.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Array Efficiency
Nov 78[1]	73.591	15.299	20.8	54.450	28.1
Dec 78	81.622	20.375	25.0	68.682	29.7
Jan 79	70.570	17.025	24.1	57.970	29.4
Feb 79	98.271	34.232	34.8	86.368	39.6
Mar 79	106.373	27.059	25.4	80.007	33.8
Apr 79	134.596	28.632	21.3	99.949	28.6
May	118.342	19.263	16.3	81.939	23.5
Jun	113.361	20.836	18.4	83.253	25.0
Jul	121.652	25.492	21.0	95.302	26.7
Aug	117.556	23.740	20.2	88.607	26.8
Sep	121.574	24.203	19.9	93.683	25.8
Total	1157.458	256.161	--	890.210	--
Average	105.223	23.287	22.5	80.928	28.8

NOTES:

(1) 20 days of data due to late start up

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 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 collector 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 being the case, there are two primary reasons for these differences;

- 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. In addition to these generic differences, the collector array at this site was built by the contractor at the time the house was constructed. Substantial variation can be expected between the "as built" configuration and the test module.

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 in this analysis.

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

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

b = Intercept on the efficiency axis

$(-)m$ = Slope

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

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

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

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

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

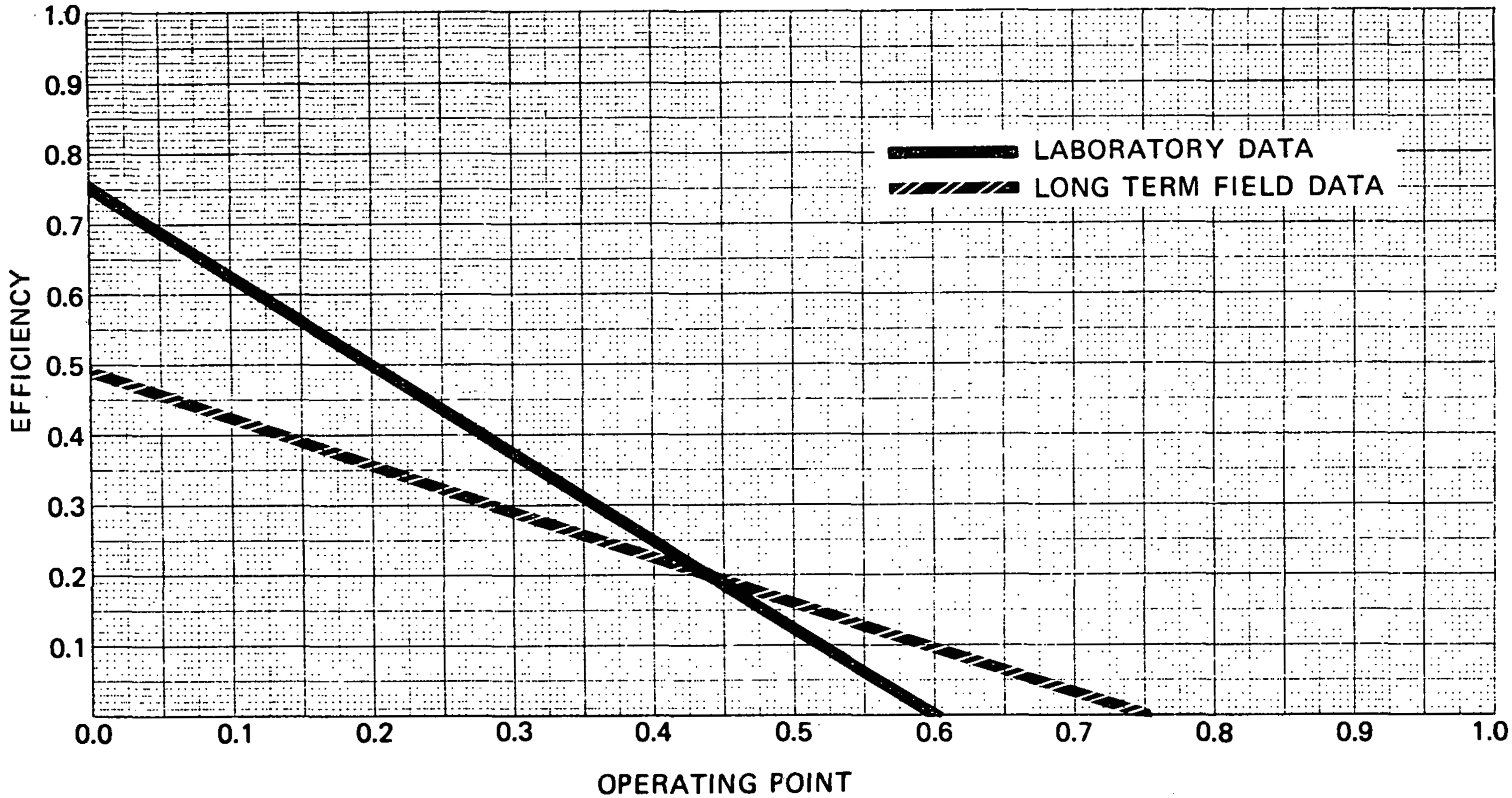
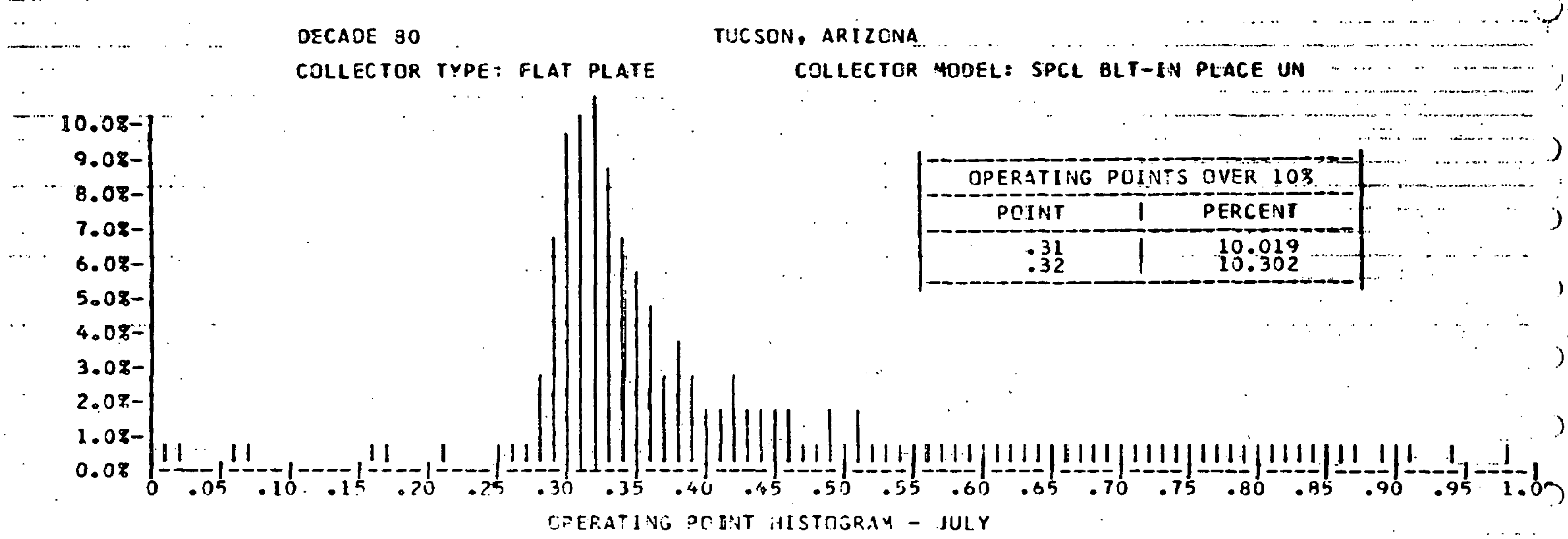


Figure 3.2.1-2 DECADE 80 HOUSE COLLECTOR EFFICIENCY CURVES



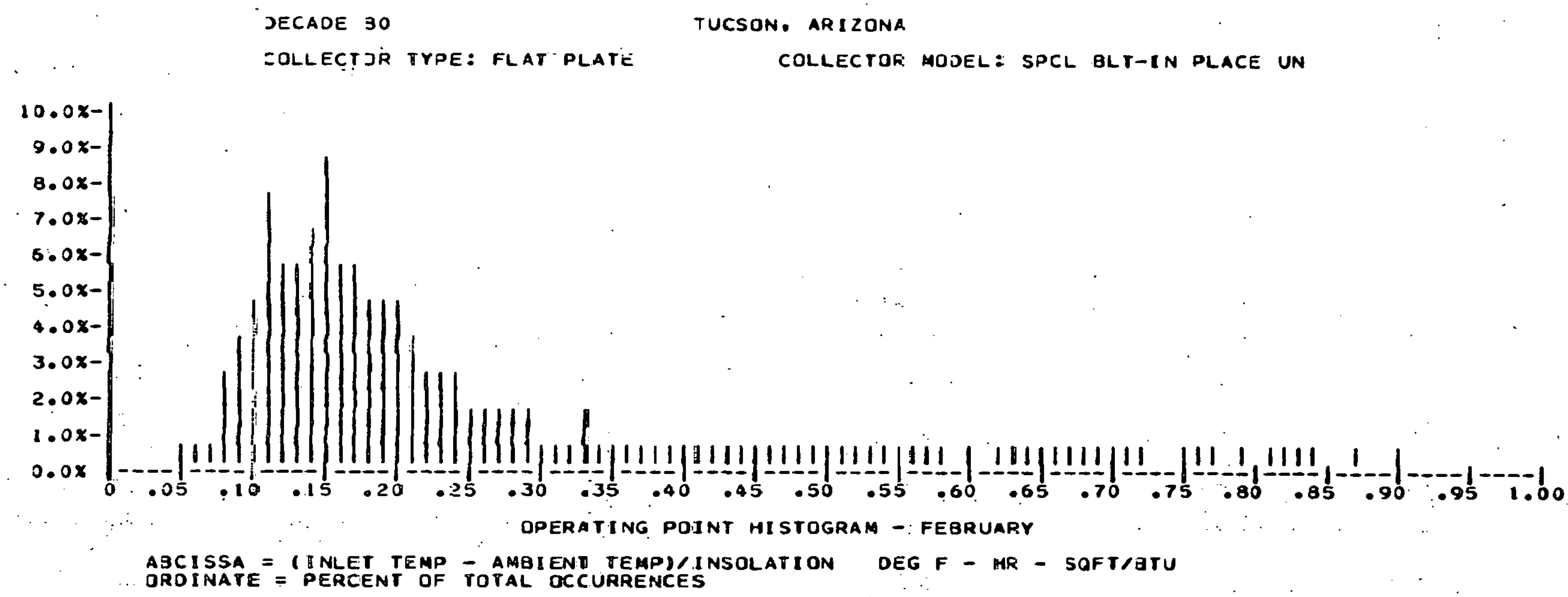


Figure 3.2.1-3 DECADE 80 HOUSE OPERATING POWER HISTOGRAMS FOR TYPICAL WINTER AND SUMMER MONTHS

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

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

where the terms are as previously defined

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

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

The two curves of Figure 3.2.1-2 show significant differences in both slope and intercept. This disparity is hardly surprising considering that the collectors at this site form an integral part of the roof and were built and installed by the construction crew at the time of the house building. A

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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.

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: DECADE 80 HOUSE TUCSON, ARIZONA

MONTH/YEAR	COLLECTED SOLAR ENERGY (MILLION BTU)	ERROR	
		FIELD DERIVED LONG TERM	LAB PANEL
NOV 78	14.69	0.147	0.242
DEC 78	19.93	0.044	-0.206
JAN 79	17.32	-0.039	-0.222
FEB 79	32.85	0.065	-0.220
MAR 79	26.70	-0.004	-0.172
APR 79	27.87	-0.005	-0.127
MAY 79	18.53	-0.007	-0.055
JUN 79	20.11	-0.008	-0.107
JUL 79	24.92	0.035	-0.072
AUG 79	22.57	0.066	-0.060
SEP 79	22.97	-0.012	-0.135
AVERAGE	22.59	0.021	-0.103

"roughly similar" Revere collector was constructed and tested prior to the home construction phase, but there is no assurance that the "as built" configuration bears any resemblance to the tested model.

Information available from the preliminary testing program using the ASHRAE method had reported an $F_R(\tau\alpha) = 0.75$ and an $F_R U_L = -1.25$, however, the long term evaluation under the present instrumentation monitoring program has yielded what must be considered a more realistic assessment of the true thermal characteristics of the operational array, e.g., $F_R(\tau\alpha) = 0.48$ and $F_R U_L = -0.64$.

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 efficiency 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:

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

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 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 Decade 80 House 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 2.1 percent. For the curve derived from the laboratory single panel data, the error was 10.3 percent. Thus the long term collector array efficiency curve gives significantly better 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 (February) and a typical summer month (July) operation. The actual midpoint which represents the average operating point for February is at 0.15 and for July at 0.35. Decade 80 House is a single family residence with hot water, space heating. and cooling systems, where the energy requirements from the solar source causes significant variation in the storage temperature. This results in the collector inlet temperature varying dependent upon the season. Consequently, the operating point changes dramatically in contrast to the less complex systems with more constant storage temperatures. For February it can be seen that both the temperature differential and the insolation used in Equation (3) are lower, as is typical during winter months; space heating enabling a greater use of the storage tank by accommodating the use of lower temperatures. As a result, the operating point range decreases and the predominant grouping shifts to the left (toward a higher efficiency). In the month of July, however, when the temperature of storage was maintained at a higher level suitable for powering the absorption chiller and the insolation was only 10 percent greater, the typical operating point moved to the right (toward the lower efficiency region). It is important to note this seasonal shift toward lower efficiency in the summer is driven primarily by the need for the higher minimum storage temperatures required by the absorption chiller. This behavior is well illustrated in Table 3.2.2-1.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the eleven 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 maximum of 0.39 in February 1979 to a minimum of 0.24 in May 1979. On the average the operational collector array efficiency exceeded the collector array efficiency, which included the effect of the control system, by 28 percent. This represents good performance for these collectors in the application which included hot water, space heating, and space cooling subsystems.

At Decade 80 House, incident solar energy totaled 1157.5 million Btu (Table 3.2.1-1) for the report period. Solar energy collected by the array totaled 256.2 million Btu, giving an overall collector array efficiency of 22.5 percent. Incident solar energy, during the time of collector loop operation, was 890.2 million Btu resulting in an operational collector efficiency of 28.8 percent. The operational collector efficiency is considered the best measure of solar system performance because it excludes such factors as control system anomalies and scheduled system down time. It, therefore, reflects the true ability of the system to collect available solar energy when it is operating in the intended collection modes.

Additional information concerning collector array analysis in general may be found in Reference [7]. The material in the reference describes the detailed collector array analysis procedures and presents the results of analyses performed on numerous collector array installations across the United States.

3.2.2 Storage Subsystem

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

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

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(s) from the primary storage medium

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

Evaluation of the system storage performance under actual system operation and weather conditions can be performed using the parameters defined above. The utility of these measured data in evaluation of the overall storage design are illustrated in the discussion which follows.

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

$$C = (Q_{si} - \Delta Q)/[(\overline{T}_s - \overline{T}_a) \times t] \frac{BTU}{Hr\text{-}°F} \tag{9}$$

where

C = Effective storage heat transfer coefficient

Q_{si} = Energy to storage

Q_{so} = Energy from storage

ΔQ = Change in stored energy

$\overline{T}_s$ = Storage average temperature

$\overline{T}_a$ = Average ambient temperature 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 eleven month average storage efficiency was 84.4 percent.

A useful application of the Effective Storage Heat Loss Coefficient is the evaluation of storage temperature for periods of time when the amounts of energy delivered to and taken from the tank are equal to each other. Such conditions did occur for a brief period from March 9 at 9 PM to March 10 at 4 AM, 1979. During this period energy to storage and energy from storage were both zero.

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
					Ambient	Storage	
Nov 78[1]	14.589	11.907	-0.273	79.7	54	139	48
Dec 78	16.684	14.182	-0.756	80.5	49	114	67
Jan 79	16.976	15.624	0.342	94.1	47	102	25
Feb 79	13.219	11.089	0.249	85.8	54	112	48
Mar 79	13.747	11.151	0.050	81.5	57	139	42
Apr 79	17.189	12.779	0.990	80.1	65	171	45
May 79	17.665	14.406	-0.058	81.2	69	176	42
Jun 79	19.922	17.659	-0.075	88.3	77	174	33
Jul 79	24.709	23.643	-0.228	94.8	81	173	20
Aug 79*	22.463	14.877	0.283	67.5	76	176	98
Sep 79*	24.709	23.643	-0.013	94.8	78	173	16
Total	201.872	170.960	0.511	--	--	--	--
Average	18.352	15.542	0.046	84.4	64	149.91	44

NOTES:

(1) 20 days actual data collected

For steady state operating conditions, the storage average temperature at the end of a time period can be determined by:

$$T_F = T_A + (T_i - T_A) \times EXP\ (- k \times t) \qquad (10)$$

where

T_F = Average temperature of storage at time t

T_A = Average ambient temperature (assumed in this case to be equivalent to the temperature in the vicinity of the storage tank)

T_i = Initial average temperature of storage at the beginning of the time period.

k = Ratio of the effective heat loss coefficient from Table 3.2.2-1 to the thermal capacity of the storage subsystem.

t = Length of time in hours

For the storage system at Decade 80 House, the 3000 gallon tank was filled with 2800 gallons of water. The thermal capacity (T_c) is:

$$T_c = 2800 \text{ gallons} \times 8.34 \text{ lbs/gallon} \times 1 \frac{\text{Btu}}{\text{lb °F}} = 23352 \frac{\text{Btu}}{\text{°F}}$$

where this is a measure of the ability of the water to store energy.

The decay constant (k) is:

k = (effective storage heat loss coefficient)/(thermal capacity)

$$k = {}^{44}/23352 = 1.8842 \times 10^{-3}/\text{hr}$$

The average temperature of storage on March 9 at 9 PM was 159.26°F and the average ambient temperature during the 7 hour period ending March 10 at 4 AM was 55.60°F. Using the equation for the T_F above

$$T_F = 55.60+(159.26 - 55.60)\text{xEXP}(-1.8842 \times 10^{-3} \times 7) = 157.9°F$$

The measured average temperature at 4 AM on March 10, 1979 was 158.03°F. This very good agreement between measured and predicted values of average storage temperatures even over this relatively brief time span lends credence to the average heat loss coefficient as presented in Table 3.2.2-1. This calculation is important since it stands in direct contrast with the specifications to which the tank was insulated, i.e., 3 inches of urethane sprayed on at construction with a published k - value of

$$0.17 \frac{\text{Btu}}{\text{hr°F ft}^2/\text{inch}}.$$

The tank of dimensions 8 1/2 feet in length and 8 1/2 feet in diameter has a surface area of 185.74 ft^2. Using the published value for the insulating property of urethane one would conclude that the R-value of the coating was 18, whereas if the calculations are based on the expected heat loss coefficient from Table 3.2.2-1 the calculated R-value is only slightly greater than 4. The disparity between these two values is significant and shows the advisability of using system characteristics based on measured data as a refinement to estimates based solely on design data.

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 Decade 80 hot water subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in this table for the months of November, December, and January contains estimations due to a faulty sensor which was repaired in early February 1979. 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 which in this instance includes losses caused by a recirculation loop which was not instrumented separately.

The measured solar fraction in Table 3.2.3-1 is an average weighted value for the month based on the ratio of solar energy in the hot water tank to the total energy in the hot water tank when a demand for hot water exists. This value is dependent on the daily profile of hot water usage.

For the eleven month period from November 1978 through September 1979, the solar energy system supplied a total of 9.21 million Btu to the hot water subsystem. The total hot water load for this period was 3.73 million Btu, and the weighted average monthly solar fraction was 62 percent.

The monthly average hot water load during the reporting period was 0.34 million Btu, which is based on an average daily consumption of 22.9 gallons, delivered at an average temperature of 126°F.

Each month an average of 0.84 million Btu of solar energy and 0.75 million Btu of auxiliary thermal electrical energy were supplied to the hot water subsystem. Since the average monthly hot water load was 0.34 million Btu, an average of 1.25 million Btu was, therefore, lost from the hot water tank each month.

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Energy Supplied (million Btu)				Hot Water Parameters			Standby Losses (1)	Weighted** Solar Fraction
	Auxiliary	Auxiliary* Thermal	Solar	Total	Gallons Used	Supply Temp (°F)	Load (million Btu)	(million Btu)	(Percent)
Nov 78	0.375(2)	0.375(2)	1.389	1.764(2)	502	113	0.098	1.666(2)	65(2)
Dec 78	1.750(2)	1.750(2)	0.207	1.957(2)	605	130	0.338	1.619(2)	45(2)
Jan 79	1.750(2)	1.750(2)	0.153	1.903(2)	699	132	0.410	1.493(2)	40(2)
Feb 79	2.390	2.390	0.468	2.858	2040	131	1.090	1.768	50
Mar 79	1.489	1.489	1.332	2.821	1649	127	0.813	2.008	58
Apr 79	0.484	0.484	1.887	2.371	1240	131	0.592	1.779	63
May 79	0.007	0.007	1.768	1.775	590	130	0.291	1.484	67
Jun 79	0	0	0.497	0.497	58	134	0.026	0.471	97
Jul 79	0	0	0.565	0.565	36	130	0.016	0.549	99
Aug 79	0	0	0.614	0.614	28	116	0.010	0.604	100
Sep 79	0.047	0.047	0.327	0.374	110	113	0.046	0.328	83
Total	8.292(2)	8.292(2)	9.207	17.499	7557	--	3.730	13.769(2)	--
Average	0.75 (2)	0.75 (2)	0.84	1.59	687	126	0.34	1.25 (2)	62

*Auxiliary Thermal (the thermal energy applied to the load)
**Weighted Solar Fraction is computed at the time hot water is actually used.

NOTES:

1. Includes losses due to recirculation system
2. Values are estimated necessitated by a non-operative instrument repaired February 6

Of the eleven months encompassed by this report, primary emphasis should be given to the three months period of February, March and April, 1979, during which the residence was occupied. Only during this time can truly representative operation of the subsystem be observed, since it is only then that the system is being used as designed.

During this period of full occupancy, an average of 55 gallons of hot water per day were consumed resulting in an average hot water load of 0.83 million Btu. The solar energy typically supplied 57 percent of the energy to produce the hot water at an average temperature of 130°F. Convenience losses from this system, which includes a recirculation loop providing instantaneously hot water upon demand, averaged 1.85 million Btu during this time.

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 Decade 80 House for the heating season, November, 1978, through April, 1979, is presented in Table 3.2.4-1. During this period, the solar energy system supplied 60.67 million Btu of a total 67.60 million Btu heating load. This represents a solar fraction of nearly 93 percent.

The long-term average number of heating degree days (based on 65°F) for the Tucson site is 1738. During the six months for which heating was required, the number of heating degree days measured at the site were 1723. This remarkably good agreement with the long-term average coupled with the high solar fraction of 93 percent shows that the heating subsystem was well designed for the locale and operated properly throughout the heating season.

TABLE 3.2.4-1

SPACE 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					
			Meas.	L.T.A.[2]				
Nov 78	9.772	71	66	59	9.772	0	0	100
Dec 78	15.054	70	49	52	13.882	2.171	3.706	86
Jan 79	18.746	70	47	51	14.946	3.799	6.316	80
Feb 79	10.842	71	54	54	10.087	0.764	1.618	93
Mar 79	9.042	71	57	58	8.836	0.205	0.364	98
Apr 79	3.147	73	65	66	3.147	0	0	100
May 79	0	77	69	74	0	0	0	0
Jun 79	0	80	77	82	0	0	0	0
Jul 79	0	82	81	86	0	0	0	0
Aug 79	0	80	76	84	0	0	0	0
Sep 79	0	80	78	80	0	0	0	0
Total	67.603	--	--	--	60.670	6.939	12.004	--
Average[1]	11.27	71	54	57	10.11	1.16	2.00	92.8

NOTES:

1. Values shown are 6 month averages (November - April)
2. L.T.A. is long-term average temperature

3.2.5 Space Cooling Subsystem

The performance of the space cooling subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space cooling load. The energy required to satisfy the load normally consists of both a solar and an auxiliary thermal component. The ratio of the cooling produced by solar energy to the total cooling load is defined as the space cooling solar fraction which is a indicator of the overall subsystem performance. The measured monthly values for performance parameters in the space cooling subsystem are presented in Table 3.2.5-1.

It was in the cooling subsystem that major modifications were made to the original design. These modifications represented the major change in the system configuration. Prior to July, 1978, the cooling subsystem contained two Arkla 501-WF direct expansion chillers which were assigned individually to east/west zones. During the summer of 1978, the system was extensively modified to incorporate the newer Model WF-36 water chiller which had been specifically designed to operate in the solar environment. Furthermore the configuration was modified so that the two chillers now operated in a primary/secondary mode with no zone dependency. With this improvement in system design, the system was operated briefly in a checkout mode November 15, 1978. There was no further requirement for cooling until April, 1979. High confidence in the data from this month is precluded due to a measurement malfunction which was directly related to the discovery of contaminants in the lines. This problem of contaminants in the generator supply lines became a recurring problem, resulting in some subsystem down time, and the necessity for estimating some of the performance parameters.

During the cooling period covered by this report a total cooling load of 75.95 million Btu was measured for an average 12.66 million Btu per month. Solar energy supplied approximately 50 percent of this load by providing energy to operate the absorption cycle of the water chiller(s). The nominal coefficient of performance for the chiller array (the chillers were not instrumented in such a manner to permit individual evaluation) was 0.46.

During August, maintenance was performed on the chillers by factory representatives who discovered two anomalies. An accumulation of non-condensible gas was present in both the chillers, which was removed by evacuation. It was also discovered that since these chillers had been designed for use in the Tucson area by having a specifically tailored refrigerant charge, they needed to operate at lower generator inlet and condenser return temperatures. Consequently the system parameter which controls generator inlet temperature was modified to prevent this over-firing which results in decreased efficiency and the dissipation of the excess heat by the cooling tower.

TABLE 3.2.5-1

SPACE COOLING SUBSYSTEM PERFORMANCE

Month	Space Cooling Load (Million Btu)	Energy Supplied (Million Btu)			Measured Solar Fraction (Percent)	Coefficient of Performance[4]
		Solar	Auxiliary Thermal	Auxiliary		
Nov 78[1]	0.038[2]	0.153[2]	0.179[2]	0.194[2]	40[2]	0.25[2]
Dec 78	0	0	0	0	0	0
Jan 79	0	0	0	0	0	0
Feb 79	0	0	0	0	0	0
Mar 79	0	0	0	0	0	0
Apr[3] 79	3.544	1.702	2.012	3.353	22	0.31
May[3] 79	7.507	17.934	4.722	7.870	73	0.57
Jun 79	15.856	21.236	21.051	31.282	47	0.32
Jul 79	21.771	24.879	26.629	44.662	49	0.40
Aug 79	13.560	13.322	10.229	17.350	56[3]	0.57
Sep 79	13.674	10.906	7.923	13.308	50[3]	0.58
Total	75.950	89.979	72.745	118.019	--	--
Average[5]	12.66	14.99	12.12	19.67	49.5	0.46

NOTES:

(1) 20 days data
(2) Test of short duration, not included in average figures
(3) Estimate due to instrumentation problem
(4) This is an array coefficient of performance, individual units could not be measured
(5) Values are 6 month averages (April-September)

4. OPERATING ENERGY

Operating energy is defined as the energy required to transport solar energy to the point of use without affecting its thermal state. Total operating energy for the Decade 80 solar energy system consists of the energy required to perform Solar Energy Collection and Storage (ECSS) operations, hot water, space heating and space cooling functions. Operating energies for the system performance evaluation period are presented in Table 4-1.

The ECSS operating energy requirement throughout the reporting period shows normal seasonal variations, e.g., expending more energy in months when there is typically more solar radiation available. On the average 0.67 million Btu per month (200 kwh) were expended for this purpose. An apparent anomaly exists in the February and March data, however, as discussed in Collector Subsystem section. This is due to the higher efficiencies of the ECSS brought about by the use of the main collector array to heat the swimming pool. This was in addition to its normal application wherein all the energy was put into the buried thermal storage.

The operating energy for the hot water subsystem was typically 0.02 million Btu per month (6 kwh). This too shows seasonal effects, but it is doubly affected since the system will only preheat water when the temperature of storage exceeds the set point of the auxiliary supplemental source in the domestic hot water tank by 10°F. During the months requiring space heating, the temperature of storage was often below this threshold value (typically 145°F). This was the principal time of occupancy; thus when the greatest demand for hot water was presented, the subsystem could not respond in the most efficient manner. Later, when the temperature of thermal storage was maintained consistently above the 145°F threshold, the demand for hot water was diminished substantially. Operating energy was expended to assist in offsetting convenience losses. It should be noted that the system contains a recirculation pump for the purpose of providing instantly available hot water at the tap. This pump was not instrumented throughout the entire season.

TABLE 4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Hot Water Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Space Cooling Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Nov 78	0.409	0.098	0.745	0.028	1.127
Dec 78	0.295	0.002	1.881	0.0	2.178
Jan 79	0.195	0.0	2.627	0.0	2.822
Feb 79	0.517	0.0	1.207	0.0	1.724
Mar 79	0.513	0.015	0.823	0.0	1.351
Apr 79	0.776	0.018	0.159	2.030	2.983
May 79	0.748	0.024	0.0	4.012	4.784
Jun 79	0.920	0.006	0.0	7.393	8.319
Jul 79	1.142	0.006	0.0	9.202	10.350
Aug 79	0.822	0.008	0.0	5.872	6.702
Sep 79	0.976	0.004	0.0	5.533	6.513
Total	7.373	0.172	7.442	34.042	48.853
Average	0.67	0.02	1.24 (1)	5.67 (2)	4.44

NOTES:

1. Values given are 6 month averages (November - April)
2. Values given are 6 month averages (April - September)

The space heating operating energy shows very good correlation with the seasonal variation in load. During the six months that space heating was required, an average 1.24 million Btu per month (365 kwh) were expended to transport heated water to the zone heat exchangers.

Space cooling operating energy also correlates well with the space cooling load. An average 5.67 million Btu per month (1661 kwh) were expended. This includes the production of chilled water as well as the distribution to the zones for actual space cooling.

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 subsystem is subtracted from the solar energy contribution. The resulting energy savings are then adjusted to reflect the thermal conversion efficiency of the auxiliary source being supplanted by solar energy. For Decade 80 the auxiliary source being supplanted in the domestic hot water subsystem is an electric immersion heater with the commonly assumed 100 percent conversion efficiency of electrical to thermal energy for such devices. For the space heating and cooling subsystems the auxiliary source being supplemented is natural gas with an assumed 60 percent conversion efficiency.

Energy savings calculated for the Decade 80 House for the period November 1978 through September 1979 are presented in Table 5-1. Note that where a subsystem had an active then inactive period, the averages only reflect the actual operational period, e.g., both the heating and cooling subsystems show 6 months averages as opposed to the ECSS system which was operational each month.

Although the site was fully occupied and used as designed only three months during this period, the hot water subsystem remained active for the entire time. A more detailed discussion of the subsystem and its operation is available in Sections 2. and 3.2.3. Because the subsystem was fully operational for the full time, an 11 month average savings of 0.801 million Btu were realized.

Two distinct seasons with different space conditioning requirements were observed. From November through much of April, space heating was required. Beginning April 18, 1979, and extending through September space cooling was required. The solar energy system was able to supply virtually all of the space heating requirement during this time.

TABLE 5-1

THERMAL ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)			Fossil Energy Savings (Million Btu)			ECSS Operating Energy (Million Btu)	Net Savings[1]			Total Net Savings (Million Btu)
								Electrical		Fossil	
	Hot Water	Space Heating	Space Cooling	Hot Water	Space Heating	Space Cooling		Million Btu	kwh	Million Btu	
Nov 78	1.282	-0.734	0.0	NA	16.287	0.0	0.409	0.139	41	16.287	16.426
Dec 78	0.199	-1.855	0.0	NA	23.137	0.0	0.295	-1.951	- 572	23.137	21.186
Jan 79	0.151	-2.590	0.0	NA	24.910	0.0	0.195	-2.634	- 772	24.910	22.276
Feb 79	0.454	-1.191	0.0	NA	16.796	0.0	0.517	-1.254	- 367	16.796	15.542
Mar 79	1.302	-0.812	0.0	NA	14.727	0.0	0.513	-0.023	- 7	14.727	14.704
Apr 79	1.829	-0.157	-2.014	NA	5.246	4.577	0.776	-1.118	- 328	9.822	8.704
May 79	1.688	0.0	-3.981	NA	0.0	29.889	0.748	-3.041	- 891	29.889	26.848
Jun 79	0.452	0.0	-7.330	NA	0.0	35.610	0.920	-7.798	-2285	35.610	27.819
Jul 79	0.547	0.0	-9.129	NA	0.0	41.465	1.142	-9.724	-2849	41.465	31.741
Aug 79	0.589	0.0	-5.872	NA	0.0	10.842	0.822	-6.105	-1789	10.842	4.737
Sep 79	0.315	0.0	-5.533	NA	0.0	18.176	0.976	-6.194	-1815	18.176	11.982
Total	8.808	-7.339	-33.859	NA	101.103	140.559	7.313	-39.703	-11634	241.661	201.965
Average	0.801	-1.223[3]	- 5.643[2]	NA	16.851[3]	23.427[2]	0.665	-3.609	-1058	21.969	18.360

NOTES:

1. Savings figures prefixed by negative signs imply losses.
2. Values given are six month averages (April-September).
3. Values given are six month averages (November-April).

Energy savings realized by offsetting the use of natural gas averaged 16.851 million Btu per month. A relatively small penalty for the application of solar energy was encountered because electricity was used to transport the energy from storage to its point of consumption. This resulted in a negative electrical savings (loss) of 1.223 million Btu per month.

Solar energy cannot be directly applied to effect space cooling since it is desirable in this instance to remove energy from the conditioned space. Because of this, solar energy is applied to an intermediate device, an absorption cycle chiller, producing cooled water which is then used to cool the space. Because devices of this type typically have an thermal efficiency less than 1.0, far more energy is used as input than is produced in the form of space cooling. Solar energy was able to supply approximately 50 percent of the energy required to cool the house from mid-April through September. This has resulted in the savings of an average 23.427 million Btu per month over the 6 month cooling season. Once again, as in the space heating discussion above, a penalty was encountered for the transport of this solar energy to its point of application. This transportation expense averaged 3.643 million Btu per month. This substantially larger transportation expense for the space cooling operation over the space heating is due to the use of larger pump which was required to supply the two chillers and the internal pumps inside the chillers.

All months experienced positive fossil savings and with the exception of November, 1979, all months experienced a negative electrical savings (losses). Total net savings are shown in Table 5-1 as 18.36 million Btu per motnh.

In order to translate the energy saving figures from Table 5-1, which are expressed in terms of thermal units, into actual costs, the rate schedule information from Appendix D was applied. Table 5-2 contains the cost savings data. In this table, the cost of the actual energy purchased is tabulated under gas or electric usage. These costs do not reflect any but those directly connected with the solar energy system, for total electric power consumption was not measured, nor was total gas usage, although no other known use of natural gas was made. Energy required without the solar energy system was projected based on equipment performance and is not an actually measured quantity.

With the exception of a relatively small amount of energy used to heat domestic hot water directly, all of the electrical energy was used in the transport of other energy forms, i.e., solar or gas heated fluids. This fact is clearly shown in the cost of operating energy and in the small electrical savings of the final column. Natural gas, which is the primary source of thermal energy at the site other than solar, is fairly inexpensive in the Tucson area, therefore, the costs savings are meager. In effect then, very little of the electrical power used could have been supplanted by solar energy since most of it went for transportation expenses. The overall cost savings at the site are also small even though solar carried 50 percent of the total load. This is primarily due to the low cost for natural gas.

Without including local taxes, the average monthly expenditure for gas and electricity actually used during the reporting period was $116.13. Had all of the energy to perform the same tasks been purchased the average monthly bill would have been $149.09 which represents a savings of $32.96/month.

Notice should be taken of the dramatic decrease in actual costs for natural gas in August. It is observed in Section 3.2.5 that chiller maintenance was performed during that time, and one of the prime discoveries was that the supply water was being over-heated, resulting in both higher thermal losses and decreased chiller efficiency.

TABLE 5-2

ACTUAL AND PROJECTED ENERGY COST COMPARISON

Month	Actual Energy Consumed (X 10^6Btu)		Actual Energy Used Cost ($)		Energy Req'd[2] W/O Solar (X 10^6Btu)	Cost of Energy W/O Solar ($)	Operating Energy Cost ($)	Total Thermal Energy Savings ($)	
	Elect	Gas[1]	Elect	Gas				Elect	Gas
Nov 78	1.502	0.0	26.16	0.0	9.77	28.26	19.96	6.20	28.26
Dec 78	3.928	3.706	56.72	11.53	16.05	43.99	36.22	20.50	32.46
Jan 79	4.632	6.316	63.28	20.28	18.75	50.69	44.61	18.67	30.41
Feb 79	3.213	1.618	53.20	8.19	10.84	31.08	29.76	23.44	22.89
Mar 79	1.835	0.0	36.17	0.0	9.04	26.62	23.72	12.45	26.62
Apr 79	2.990	3.353	50.45	11.94	8.20	24.54	46.60	3.85	12.60
May 79	4.784	7.870	84.51	24.73	25.80	68.16	84.51	0.0	43.43
Jun 79	8.319	31.282	141.81	81.75	52.65	134.72	141.81	0.0	52.47
Jul 79	10.350	44.662	174.81	114.91	69.54	167.66	174.81	0.0	52.75
Aug 79	5.928	17.350	119.29	47.22	30.67	80.24	119.24	0.0	33.02
Sep	6.560	13.308	113.30	37.20	24.21	64.20	112.52	0.78	37.00
Total	55.041	129.465	919.70	357.75	275.52	720.16	833.76	85.89	371.91
Average	5.0	11.77	83.61	32.52	25.05	65.47	75.80	7.81	33.81

NOTES:

(1) Energy as measured at meter, not as supplied to conditioned space
(2) Projected energy requirement had solar not been available, includes only subsystems using gas

6. MAINTENANCE

This section includes the solar energy system maintenance performed during this seasonal report period, November 1978 through September 1979. Maintenance data on the instrumentation system is not included in this report.

December 1978 - During a particularly cold night while circulating water through the ECSS heat exchanger, the heat exchanger cracked a header. This damage was assessed as relatively minor and system operation was not materially affected. Repairs were completed during January 1979.

January 1979 - An additional heat exchanger was installed in the ECSS loop to provide heating for the swimming pool. Use was begun on February 7, 1979.

May 1979 - Pump P4 was changed from 1 hp to 1/4 hp to conserve energy.

August 1979 - Representatives of Arkla, Incorporated, the chiller manufacturer, installed flow feed-back loops to help control temperatures entering generators of both absorption chillers. In addition, flow limiting orifices were installed in the generator inlets and the outlet load line to hold flow to specified levels.

August 1979 - Galvanic action caused by dissimilar metals used in solar energy system plumbing caused disruption of flows and required that the system be flushed. The principal effect was noticed in the uncertainty of measurements in the cooling subsystem. It was concluded that no serious damage was done to any part of the solar energy system.

7. SUMMARY AND CONCLUSIONS

For the report period November 1978 through September 1979, the average measured daily incident solar energy in the plane of the collector was 1801 Btu/ft^2 which was about 11 percent below the long-term value. The average daily outdoor ambient temperature was 64°F, which is nearly 5°F less than the long-term average of 69°F. Based solely on these conditions loads at the site were expected to be slightly less than designed.

The incident solar energy for the 11 month period totaled 1157.5 million Btu. Operational solar energy totaled 890.2 million Btu and the total collected solar energy totaled 256.2 million Btu. This gives a collector operational efficiency of 28.8 percent. The collector array efficiency was 22.5 percent. The 23 percent difference between the incident and operational incident solar energy is an anticipated value which indicates the control system is operating in the expected manner. Collector analysis data indicates the collector is operating at an efficiency which is significantly less than was expected. This is attributed primarily to the fact that the collectors which were built in place at the time of construction did not match the prototype which was used for testing, and upon which performance expectations were based.

The average hot water load during this 11 month period was 0.34 million Btu per month. This is based on an average consumption of 687 gallon per month at an average usage temperature of 126°F. This very low figure is indicative of the fact that the home was unoccupied for most of the test period. While full occupancy existed, more normal usage profiles were observed; e.g., 1643 gallons of hot water were used per month, at 130°F. This is normal usage for two person occupancy. Overall, the hot water subsystem provided 62 percent of the hot water, but during the three months of full occupancy, the fraction was only 57 percent.

Space heating was required during six months of the reporting period. The solar energy system supplied 93 percent of the total space heating requirement during this time. During the three months of full occupancy, however, the system supplied 97 percent of the space heating requirements. This performance is outstanding when compared with the predicted performance using the modified f-Chart approach where only a 76 percent contribution was expected.

Space cooling was required for six months of the test period. Although the home was not actually occupied during any appreciable length of time during which space cooling was required, the system remained under automatic thermostat control in order to obtain cooling season data. Very good agreement with expected loads based on long-term average cooling degree day data were found. The measured solar fraction for the six months of cooling was 48 percent, compared with the expected solar fraction of 63 percent. The 23 percent lower than expected solar fraction is directly related to the 11 percent lower than expected incident solar radiation and the low COP of the absorption chiller array prior to this repair in early August 1979.

The use of solar energy in this installation has resulted in the net savings of non-renewable energy supplies. Over the 11-months of the study a total of 201.97 million Btu were saved. Although most of this savings was actually realized by offsetting the need for burning natural gas, the savings would have been an average of 5380 kwh/month had the auxiliary been electricity. Table 5-1 shows that there was a net loss associated with the actual use of electricity primarily due to the fact that it was employed as an operating energy source to transport other forms of energy and did not contribute to the change in thermal state of any of the subsystems.

The Decade 80 House was designed and built in the mid-70's to be a showplace/ workshop for solar energy utilization. Superior construction techniques, the use of quality materials and a full time maintenance staff have served to make the entire system an outstanding example of the application of solar energy for residential purposes. The luxury of a full time, on-site maintenance person is perhaps the single most important aspect of this program. While most installations can not support this level of maintenance, in the early stages of this emerging industry it has been very useful in order to keep all subsystems operating in top form and to allow for a full season data collection to be obtained.

Several conclusions may be drawn from this long term monitoring effort, among which are:

- Flat plate collectors will support space cooling
- Definite energy savings can be realized
- More frequent periodic maintenance may be required on solar energy systems that are not custom built

Some specific subsystem recommendations may also be made. From a purely conservationist point of view the recirculation hot water loop should be eliminated, since its convenience contributes to a higher loss for that subsystem which can not be directly made up by solar energy. Full use of the main collector array to heat the pool should always be considered. This application significantly improved the collector array efficiency and extended the pool use season. Consideration should be given to the addition of some cold thermal storage which would provide a buffer capacitance between space cooling used and ability to produce chilled water. Further analysis, beyond the scope of this report would be required to properly size that cold thermal storage. Although the concept of primary/secondary chiller operation appeared to work well, perhaps a better utilization of the operating energy would have been made had the two chillers been arranged for separate supply. The use of one pump capable of supplying full flow when both chillers were on to supply only one chiller resulted in a poor energy efficiency ratio (EER). The frequent cycling seen in the space heating subsystem (Figure 2.2-1) may have been caused by a poor heat anticipator setting or high infiltration rates. An investigation of either of these occurrences is in order.

In conclusion, considering the complexity of this site and its overall record of consistent daily operation; meeting a very high fraction of all loads; the Decade 80 House must be rated as an outstanding example of the applications of solar energy to residential systems.

8. REFERENCES

1. DOE/NASA CR-150851, Instrumentation at the "Decate 80" Solar House in Tucson, Arizona (Collation of Monthly Reports), October 1978

2. DOE/NASA CR-150869, Final System Instrumentation Design Package For Decade 80 Solar House, December 1978

3. J. T. Smok, V. S. Sohoni, J. M. Nash, "Processing of Instrumented Data for the National Solar Heating and Cooling Demonstration Program," Conference on Performance Monitoring Techniques for Evaluation of Solar Heating and Cooling Systems, Washington, D.C., April, 1978.

4. E. Streed, et. al., Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program, NBS-IR-76-1137, National Bureau of Standards, Washington, August, 1976.

5. ASHRAE Standard 93-77, Methods of Testing to Determine the Thermal Performance of Solar Collectors, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

6. ASHRAE Standard 94-77, Methods of Testing Thermal Storage Devices Based on Thermal Performance, The American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

7. McCumber, W. H. Jr., "Collector Array Performance for Instrumented Sites of the National Solar Heating and Cooling Demonstration Program," SOLAR/0021-79/38 published and distributed at the 1979 Solar Update Conference.

8. Beckman, William A.; Klein, Sanford A.; Duffie, John A., Solar Heating Design by the f-Chart Method. John Wiley and Sons, New York, 1977.

9. Mears, J. C. and Nash, J. M.; Performance Evaluation of Solar Energy Systems Using a Modified f-Chart Analysis, presented to the Semi-annual ASHRAE meeting, February, 1980.

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS

FOR

SOLAR TERMS

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

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

- INCIDENT SOLAR ENERGY 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 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 is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY 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.

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 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 is the average temperature of the outdoor environment at the site.

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

- AUXILIARY THERMAL ENERGY TO ECSS 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 is the critical operating energy required to support the ECSS heat transfer loops.

STORAGE PERFORMANCE

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

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

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

- CHANGE IN STORED ENERGY 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 is the mass-weighted average temperature of the primary storage medium.

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

- HOT WATER LOAD 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 is the percentage of the load demand which is supported by solar energy.

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

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

- AUXILIARY THERMAL USED 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 is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS 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 is the average inlet temperature of the water supplied to the subsystem.

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

- HOT WATER USED is the volume of water used.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors similar to those of the hot water subsystem, described above. The average building temperature and the average ambient temperature are tabulated again on this form to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space. The performance factors provided on this report are defined as follows:

- SPACE HEATING LOAD is the sensible energy added to the air in the building.
- SOLAR FRACTION OF LOAD is the percentage of the load demand which is supported by solar energy.
- SOLAR ENERGY USED is the amount of solar energy supplied to the space heating subsystem.
- OPERATING ENERGY 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 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 is the amount of fossil fuel energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS 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.

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

- BUILDING TEMPERATURE is the average space heated area dry bulb temperature.

- AMBIENT TEMPERATURE is the average ambient dry bulb temperature at the site.

SPACE COOLING SUBSYSTEM

The space cooling subsystem is characterized by performance factors similar to those of the hot water subsystem and space heating subsystem, described previously. The performance factors in this form are defined as follows:

- SPACE COOLING LOAD is the total energy, including sensible and latent, removed from the air in the spaced-cooled are of the building.

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

- SOLAR ENERGY USED is the amount of solar energy supplied to the space-cooling subsystem.

- <u>OPERATING ENERGY</u> is the amount of electrical energy required to support the subsystem, e.g., fans, pumps, etc., and which is not intended to directly effect the thermal state of the subsystem.

- <u>AUXILIARY THERMAL USED</u> 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>AUXILIARY ELECTRICAL FUEL</u> is the amount of electrical energy supplied directly to the subsystem.

- <u>AUXILIARY FOSSIL FUEL</u> is the amount of fossil fuel energy supplied directly to the subsystem.

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

- <u>FOSSIL ENERGY SAVINGS</u> is the estimated difference between the fossil energy requirements of the alternative conventional system (carrying the full load) and the actual fossil energy requirements of the subsystem.

- <u>BUILDING DRY BULB TEMPERATURE</u> is the average dry bulb temperature of the conditioned space.

- <u>AMBIENT TEMPERATURE</u> is the average ambient dry bulb temperature at the site.

THERMODYNAMIC CONVERSION EQUIPMENT

The performance of all thermodynamic cycle equipment (e.g., heat pumps, absorption chillers) used to transform energy at one temperature to energy at another temperature will be reported by the following parameters. The performance is characterized by the energies flowing to and from the equipment and the coefficient of performance of the equipment.

The performance factors are defined as follows:

- EQUIPMENT LOAD is the controlled energy output of thermodynamic conversion equipment.
- THERMAL ENERGY INPUT is the equivalent thermal energy which is supplied as a fuel source to thermodynamic conversion equipment.
- OPERATING ENERGY is the amount of energy required to support the operation of thermodynamic conversion equipment which is not intended to appear directly in the load.
- ENERGY REJECTED is the amount of energy intentionally rejected or dumped from thermodynamic conversion equipment as a by-product or consequence of its principal operation.
- COEFFICIENT OF PERFORMANCE is the coefficient of performance of the thermodynamic conversion equipment.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site. It is tabulated for two purposes (1) as a measure of the conditions prevalent during the operation of the system at the site, and (2) as a historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION is the accumulated total solar energy incident upon the gross collector array measured at the site.
- AMBIENT TEMPERATURE(TA) is the average temperature of the environment at the site.
- DAYTIME AMBIENT TEMPERATURE 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

DECADE 80 HOUSE

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR DÉCADE 80 HOUSE

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. Examples of these general forms are as follows: The total solar energy available to the collector array is given by

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

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

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

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

For a liquid system ΔH is generally given by

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

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 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." [4] 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 Decade 80 House used for the data evaluation of this report are contained in the following pages and have been included for technical reference and information.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

SITE SUMMARY REPORT:

INCIDENT SOLAR ENERGY (BTU)

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

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

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

COLLECTED SOLAR ENERGY (BTU)

= $\Sigma [M100 \times CP21 \times (T100 - T150)] \times \Delta\tau$

WHERE CP21 IS THE SPECIFIC HEAT VALUE OF THE HEAT TRANSFER FLUID AS A FUNCTION OF TEMPERATURE

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

= $\Sigma [M100 \times CP21 \times (T100 - T150)/AREA] \times \Delta\tau$

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

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

SOLAR ENERGY TO LOAD (BTU)

= $\Sigma [M403 \times HWD(T453, T403) + (M300 + M301) + HWD(T350, T300)] \times \Delta\tau$
+ POOL HEATING LOAD

WHERE HWD(T1, T2) IS A FUNCTION WHICH CALCULATES THE ENTHALPY DIFFERENCE AT T1 AND T2 FOR WATER

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

COLLECTOR ARRAY EFFICIENCY = SOLAR ENERGY COLLECTED/INCIDENT SOLAR ENERGY

OPERATIONAL INCIDENT SOLAR ENERGY (BTU/SQ FT)

= $1/60 (I001 \times AREA) \times \Delta\tau$, WHENEVER COLLECTOR PUMP IS RUNNING

ECSS OPERATING ENERGY (BTU)

= Σ [CONST x EP600 -HEATING OPERATING ENERGY -HOT WATER OPERATING ENERGY] x $\Delta\tau$

WHERE CONST = 3413/60

LOAD SUBSYSTEM SUMMARY:

HOT WATER SUBSYSTEM:

HOT WATER AUXILIARY ELECTRICAL ENERGY (BTU)

= CONST Σ(EP300) x $\Delta\tau$

HOT WATER AUXILIARY THERMAL ENERGY = HOT WATER AUXILIARY ELECTRICAL ENERGY

POOL HEATING LOAD = Σ[M100 X HWD(T560, T561)] x $\Delta\tau$

ENERGY TO STORAGE (BTU)

= Σ[M200 x HWD(T250, T200)] x $\Delta\tau$

ENERGY FROM STORAGE (BTU)

= Σ[M403 x HWD(T453, T403) + (M300 + M301) x HWD(T350, T300)] x $\Delta\tau$

CHANGE IN STORED ENERGY (BTU)

= STORAGE CAPACITY x [HEAT CONTENT PREVIOUS HOUR - HEAT CONTENT PRESENT HOUR]

WHERE STORAGE CAPACITY IS THE ACTIVE VOLUME OF THE TANK

STORAGE AVERAGE TEMP (DEGREE F)

= (1/60) Σ [(T201 + T202 + T203) / 3] x $\Delta\tau$

STORAGE EFFICIENCY

= (CHANGE IN STORED ENERGY + ENERGY FROM STORAGE)/ENERGY TO STORAGE

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

DAYTIME AMBIENT TEMP (DEGREE F)

= (1/360) Σ [T001] x $\Delta\tau$

(COMPUTED ONLY $\pm$ 3 HOURS FROM SOLAR NOON)

HOT WATER OPERATING ENERGY (BTU) = CONST Σ [EP600] x $\Delta\tau$

HOT WATER AUXILIARY ELECTRIC FUEL (BTU)

= Σ [(EPCONST) x EP300] x $\Delta\tau$

TEMPERATURE OF COLD WATER SUPPLY (°F)

= TSW2/TSW1 (PERFORMED AT THE END OF EACH HOUR)

WHERE TSW2 = Σ M301 x T351 x $\Delta\tau$

TSW1 = Σ M301 x $\Delta\tau$

TEMPERATURE OF HOT WATER SUPPLY (°F) = THW1/TSW1 (PERFORMED AT END OF EACH HOUR)

WHERE THW1 = Σ [M301 x T301] x Δτ

HOT WATER LOAD

= Σ [M301 x HWD(T301, T351)] x Δτ

HOT WATER ELECTRICAL SAVINGS

= Σ [(M300 + M301) x HWD(T350 -T300)] x Δτ - CONST Σ [EP600] x Δτ

HOT WATER SOLAR FRACTION (PERCENT)

= 100 x (HOT WATER SOLAR ENERGY SUPPLIED TO CONSUMPTION LOAD/ HOT WATER LOAD)

HOT WATER CONSUMPTION (GAL) = Σ [WD301] x Δτ

WHERE WD301 IS HOT WATER CONSUMPTION RATE DERIVED FROM W301

SYSTEM PERFORMANCE FACTOR

= SYSTEM LOAD/3.33 x (AUXILIARY ELECTRIC FUEL + SYSTEM OPERATING ENERGY)

SPACE HEATING SUBSYSTEM:

SPACE HEATING LOAD

= Σ [(M504) x HWD(T504, T554)] x Δτ

AUXILIARY SPACE HEATING THERMAL ENERGY

= Σ [(M504) x HWD(T402, T554)] x Δτ

SPACE HEATING SOLAR ENERGY

= SPACE HEATING LOAD - SPACE HEATING AUXILIARY THERMAL ENERGY

SPACE HEATING SOLAR FRACTION

= SPACE HEATING SOLAR ENERGY/SPACE HEATING LOAD

SPACE HEATING ELECTRICAL SAVINGS

= CONST x Σ [EP600] x Δτ

SPACE HEATING FOSSIL SAVINGS

= SPACE HEATING SOLAR ENERGY/0.6

SPACE HEATING FOSSIL ENERGY

$$= \frac{\text{(HEATING AUXILIARY FOSSIL ENERGY)x(TOTAL AUXILIARY FOSSIL ENERGY)}}{\text{(HEATING AUXILIARY THERMAL ENERGY)+(COOLING AUXILIARY THERMAL ENERGY)}}$$

SPACE HEATING OPERATING ENERGY

= CONST Σ [EP600] x Δτ

SPACE COOLING SUBSYSTEM:

COOLING LOAD = Σ [M504 x HWD(T554, T504)] x $\Delta\tau$

COOLING AUXILIARY THERMAL ENERGY

= Σ [((M500 + M501) x CP x T402 -((M500 x CP x T500) + (M501 x CP x T501)))] x $\Delta\tau$

COOLING OPERATING ENERGY

= CONST Σ [EP500 + EP601] x $\Delta\tau$

COOLING SOLAR FRACTION

= 100 x (COOLING ENERGY/COOLING SOLAR ENERGY + COOLING AUXILIARY THERMAL ENERGY)

COOLING AUXILIARY FOSSIL ENERGY

= (COOLING AUXILIARY THERMAL ENERGY x TOTAL AUXILIARY FOSSIL ENERGY) / (HEATING AUXILIARY THERMAL ENERGY + COOLING AUXILIARY THERMAL ENERGY)

COOLING ELECTRICAL SAVING

= Σ [CONST x EP500] x $\Delta\tau$

COOLING FOSSIL SAVINGS

= (COOLING SOLAR ENERGY)/0.6

COOLING SOLAR ENERGY

= INPUT TO THERMODYNAMIC CONVERSION EQUIPMENT - COOLING AUXILIARY THERMAL ENERGY

THERMODYNAMIC CONVERSION EQUIPMENT INPUT

= Σ [W502 x HWD(T550, T502) + M503 x HWD(T553, T503)] x $\Delta\tau$

THERMODYNAMIC CONVERSION EQUIPMENT REJECTED ENERGY

= Σ [M502 x HWD(T550, T502) + M503 x HWD (T553, T503)] x $\Delta\tau$

THERMODYANMIC EQUIPMENT LOADS = COOLING LOAD

THERMODYNAMIC EQUIPMENT COEFFICIENT OF PERFORMANCE

= THERMODYNAMIC EQUIPMENT LOAD / THERMODYNAMIC EQUIPMENT INPUT ENERGY

COOLING SOLAR ENERGY = THERMODYNAMIC EQUIPMENT ENERGY - COOLING AUXILIARY THERMAL ENERGY

SYSTEM LOAD = HOT WATER LOAD + SPACE HEATING LOAD + SPACE COOLING LOAD + POOL HEATING LOAD

SYSTEM OPERATING ENERGY = HOT WATER OPERATING ENERGY + SPACE COOLING OPERATING ENERGY + SPACE COOLING OPERATING ENERGY + ECSS OPERATING ENERGY

AUXILIARY THERMAL ENERGY = HOT WATER AUXILIARY THERMAL + SPACE HEATING AUXILIARY THERMAL + SPACE COOLING AUXILIARY THERMAL

AUXILIARY ELECTRICAL ENERGY = HOT WATER AUXILIARY ELECTRIC ENERGY

SYSTEM SOLAR FRACTION = (HOT WATER LOAD x HOT WATER SOLAR FRACTION + SPACE HEATING LOAD x SPACE HEATING SOLAR FRACTION + SPACE COOLING LOAD x SPACE COOLING SOLAR FRACTION + POOL HEATING LOAD)/TOTAL SYSTEM LOAD

TOTAL ELECTRICAL SAVINGS = HOT WATER ELECTRICAL SAVINGS + HEATING ELECTRICAL SAVINGS - ECSS OPERATING ENERGY + COOLING ELECTRICAL SAVINGS

TOTAL FOSSIL SAVINGS = HEATING FOSSIL SAVINGS + COOLING FOSSIL SAVINGS

TOTAL ENERGY CONSUMED = AUXILIARY ELECTRIC ENERGY + AUXILIARY FOSSIL ENERGY + SYSTEM OPERATING ENERGY + SOLAR ENERGY COLLECTED

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

APPENDIX C

LONG TERM AVERAGE WEATHER CONDITIONS

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

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

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

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

SITE: DECADE 80 22. LOCATION: TUCSON AZ

ANALYST: C. WALLACE FDRIVE NO.: 56.

COLLECTOR TILT: 26.50 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 32.00 (DEGREES) RUN DATE: 01/28/80

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1751.	1099.	0.62755	1.473	1613.	442	0	51.
FEB	2174.	1431.	0.65797	1.322	1892.	333	11	54.
MAR	2688.	1866.	0.69408	1.167	2173.	243	13	58.
APR	3179.	2363.	0.74339	1.026	2425.	81	96	66.
MAY	3490.	2673.	0.76586	0.925	2475.	0	272	74.
JUN	3604.	2728.	0.75709	0.885	2414.	0	513	82.
JUL	3539.	2341.	0.66163	0.909	2127.	0	660	86.
AUG	3290.	2183.	0.66335	0.980	2133.	0	583	84.
SEP	2859.	1980.	0.69250	1.106	2189.	0	453	80.
OCT	2320.	1604.	0.69130	1.276	2047.	29	187	70.
NOV	1847.	1209.	0.65463	1.441	1742.	221	26	59.
DEC	1630.	995.	0.61087	1.517	1510.	403	0	52.

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.

APPENDIX D

UTILITY RATE SCHEDULES FOR
GAS AND ELECTRICITY IN
TUCSON, ARISONA

TUCSON ELECTRIC POWER COMPANY
P. O. Box 711
Tucson, Arizona 85702

Dear Customer:

At your request we submit our Residential Electric Rate No. 1 showing current adjustments:

RESIDENTIAL ELECTRIC RATE NO. 1

		Base Rate
SUMMER -		
May through October billings		
First 100 kwh or less per month		$6.88
All additional kwh per month	@	5.0841¢ per kwh
WINTER -		
November through April billings		
First 100 kwh or less per month		$6.88
Next 500 kwh per month	@	5.0841¢ per kwh
Next 400 kwh per month	@	3.7733¢ per kwh
All additional kwh per month	@	2.7293¢ per kwh
Fuel and Purchased Power Cost Adjustment:		
All kwh per month	@	.45264¢ per kwh

Minimum Bill: $6.88 per month per meter.

TUCSON: To calculations on above rates add 2.0% Franchise Tax; then, to calculations on above rates plus Franchise Tax add 6.224% Sales Taxes and Corporation Commission Assessment.

SOUTH TUCSON: To calculations on above rates add 6.224% Sales Taxes and Corporation Commission Assessment.

OTHER: To calculations on above rates add 4.216% Sales Taxes and Corporation Commission Assessment.

There shall be a $10.55 charge for the initial establishment of each new service for each customer. There shall be a $10.55 charge for the re-establishment of each service for each customer.

Very truly yours,

TUCSON ELECTRIC POWER COMPANY

Eff. January 1980

SOUTHWEST GAS CORPORATION
Las Vegas, Nevada
Arizona Gas Tariff
Southern Arizona Division

Fourth Revised A.C.C. Sheet No. 9
Cancelling Third Revised A.C.C. Sheet No. 9

STATEMENT OF RATES
EFFECTIVE RATES APPLICABLE TO SOUTHERN ARIZONA DIVISION SCHEDULES[1/]

Schedule No. & Type of Charge	Base Tariff Rate	Fuel Adjustment Current	Fuel Adjustment Cumulative	Currently Effective Tariff Rate
G-60				
Summer (June-September)				
Priority 1				
Commodity Charge				
First 5 Ccf or Less	$2.50	$ --	$ --	$2.50
Plus Fuel Adj. per Ccf	--	.01184	.05621	.05621
Next 20 Ccf per Ccf	.29530	.01184	.05621	.35151
Next 25 Ccf per Ccf	.22679	.01184	.05621	.28300
All Additional Ccf per Ccf	.19167	.01184	.05621	.24788
Winter (October-May)				
Priority 1				
Commodity Charge				
First 5 Ccf or Less	$2.50	$ --	$ --	$2.50
Plus Fuel Adj. per Ccf	--	.01184	.05621	.05621
Next 20 Ccf per Ccf	.29530	.01184	.05621	.35151
Next 75 Ccf per Ccf	.22679	.01184	.05621	.28300
Next 400 Ccf per Ccf	.21227	.01184	.05621	.26848
Next 1,000 Ccf per Ccf	.19786	.01184	.05621	.25407
All Additional Ccf per Ccf	.19167	.01184	.05621	.24788
G-70				
Summer (June-September)				
Priority 1 and 2				
Commodity Charge				
First 5 Ccf or Less	$2.50	$ --	$ --	$2.50
Plus Fuel Adj. per Ccf	--	.01184	.05621	.05621
Next 20 Ccf per Ccf	.29530	.01184	.05621	.35151
Next 75 Ccf per Ccf	.22679	.01184	.05621	.28300
Next 400 Ccf per Ccf	.21227	.01184	.05621	.26848
All Additional Ccf per Ccf	.19167	.01184	.05621	.24788
Priority 3				
Commodity Charge				
First 5 Ccf or Less	$2.50	$ --	$ --	$2.50
Plus Fuel Adj. per Ccf	--	.00039	.09142	.09142
Next 20 Ccf per Ccf	.29530	.00039	.09142	.38672
Next 75 Ccf per Ccf	.22679	.00039	.09142	.31821
Next 400 Ccf per Ccf	.21227	.00039	.09142	.30369
All Additional Ccf per Ccf	.19167	.00039	.09142	.28309

Issued On: November 29, 1979

Issued by
Marvin R. Shaw
Vice President

Effective: January 1, 1980

SOUTHWEST GAS CORPORATION
Las Vegas, Nevada
Arizona Gas Tariff — Fourth Revised A.C.C. Sheet No. 10
Southern Arizona Division — Cancelling Third Revised A.C.C. Sheet No. 10

STATEMENT OF RATES
EFFECTIVE RATES APPLICABLE TO SOUTHERN ARIZONA DIVISION SCHEDULES[1/]
(Continued)

Schedule No. & Type of Charge	Base Tariff Rate	Fuel Adjustment Current	Fuel Adjustment Cumulative	Currently Effective Tariff Rate
G-70 (Continued)				
Winter (October-May)				
Priority 1 and 2				
Commodity Charge				
First 5 Ccf or Less	$2.50	$ --	$ --	$2.50
Plus Fuel Adj. per Ccf	--	.01184	.05621	.05621
Next 20 Ccf per Ccf	.29530	.01184	.05621	.35151
Next 75 Ccf per Ccf	.22679	.01184	.05621	.28300
Next 400 Ccf per Ccf	.21227	.01184	.05621	.26848
Next 1,000 Ccf per Ccf	.19786	.01184	.05621	.25407
All Additional Ccf per Ccf	.19167	.01184	.05621	.24788
Priority 3				
Commodity Charge				
First 5 Ccf or Less	$2.50	$ --	$ --	$2.50
Plus Fuel Adj. per Ccf	--	.00039	.09142	.09142
Next 20 Ccf per Ccf	.29530	.00039	.09142	.38672
Next 75 Ccf per Ccf	.22679	.00039	.09142	.31821
Next 400 Ccf per Ccf	.21227	.00039	.09142	.30369
Next 1,000 Ccf per Ccf	.19786	.00039	.09142	.28928
All Additional Ccf per Ccf	.19167	.00039	.09142	.28309
G-75				
Priority 1				
Hourly Rated Capacity Per Lamp per Month	$1.57	$ .086	$ .410	$1.980
G-80				
Priority 2				
Commodity Charge				
First 2,500 Mcf per Month	$1.7743	$ .1184	$ .5621	$2.3364
Next 47,500 Mcf per Month	1.7423	.1184	.5621	2.3044
All Additional Mcf per Month	1.7333	.1184	.5621	2.2954
Priority 3				
Commodity Charge				
First 2,500 Mcf per Month	$1.7743	$ .0039	$ .9142	$2.6885
Next 47,500 Mcf per Month	1.7423	.0039	.9142	2.6565
All Additional Mcf per Month	1.7333	.0039	.9142	2.6475

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