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REPORT

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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL  
REPORT FOR ELCAM SAN DIEGO, SAN DIEGO, CALIFORNIA

Prepared by

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For the U. S. Department of Energy



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Solar Energy

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## 1. FOREWORD

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

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

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

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

The Seasonal Report document in conjunction with the Final Report for each Operational Test Site in the Development Program culminates the technical activities which began with the site selection and instrumentation system design in April 1976. The Final Report emphasizes the economic analysis of solar systems performance and features payback performance based on life cycle costs for the same solar system in various geographic regions. Another document specifically related to this system is Reference [1].

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\*Number in bracket designate reference found in Section 8.

## 2. SYSTEM DESCRIPTION

The Elcam San Diego Solar Energy System provides domestic hot water heating for a single family residence located in Encinitas, California. The system is a "Sunspot" two tank cascade type, where solar energy is supplied to either a 66 gallon preheat tank (solar storage) or a 40 gallon domestic hot water tank. The temperatures of the water in the collectors, the preheat tank, and the domestic hot water tank are measured, and the controller is programmed to pump water from either the preheat tank or the domestic hot water tank through the collectors and back to the same tank depending on the measured temperatures. At preset tank temperatures or temperature differences between the tank and collector water, the controller will switch the cascade valve to divert the flow to the alternate tank until the water in that tank has reached a preset temperature or temperature difference between tank and collector temperatures. Freeze protection is provided by the controller actuating the pump and circulating hot water from the domestic hot water tank through the collectors when collector temperatures approach freezing. The collector array points 15 degrees west of south at a tilt of 18.5 degrees. The collector cover is one eighth inch tempered glass. Auxiliary energy is supplied by natural gas.

Figure 2-1 is a schematic of the Elcam San Diego System. The sensor designations are in accordance with NBS-IR-76-1137. Figure 2-2 is a pictorial view of the Elcam San Diego site.

The Elcam San Diego Solar Energy System has the following modes of operation:

Mode 1 - Collector-to-Domestic Hot Water Tank: This mode takes precedence over all modes and is initiated whenever the difference in temperature between the bottom of the domestic hot water tank and collector outlet temperature exceeds 20°F and when the temperature in this tank is less than 140°F. This mode continues until the temperature difference between tank bottom and collector outlet drops to less than 3°F or until the tank temperature exceeds 140°F.



Mode 2 - Collector-to-Solar Storage Tank: This mode is initiated whenever the difference between the water in the bottom of the solar storage tank and the collector outlet temperature exceeds 20°F, or when the temperature in the domestic hot water tank exceeds 140°F and the collector outlet temperature exceeds the solar tank bottom by 20°F. This mode continues until the temperature difference between collector outlet and solar tank bottom falls to 3°F, or until Mode 1 is initiated by the collector outlet temperature exceeding the domestic hot water tank bottom by 20°F when domestic hot water is less than 140°F.

Mode 3 - Auxiliary: This mode is initiated whenever the temperature in the domestic hot water tank falls below 105°F at which time energy is then transferred to the domestic hot water tank by burning natural gas.

• I001 - COLLECTOR PLANE  
TOTAL INSOLATION

• T001 - OUTDOOR TEMPERATURE

**LEGEND**  
T = TEMPERATURE  
W = FLOWRATE  
EP = ELECTRIC POWER  
I = INSOLATION

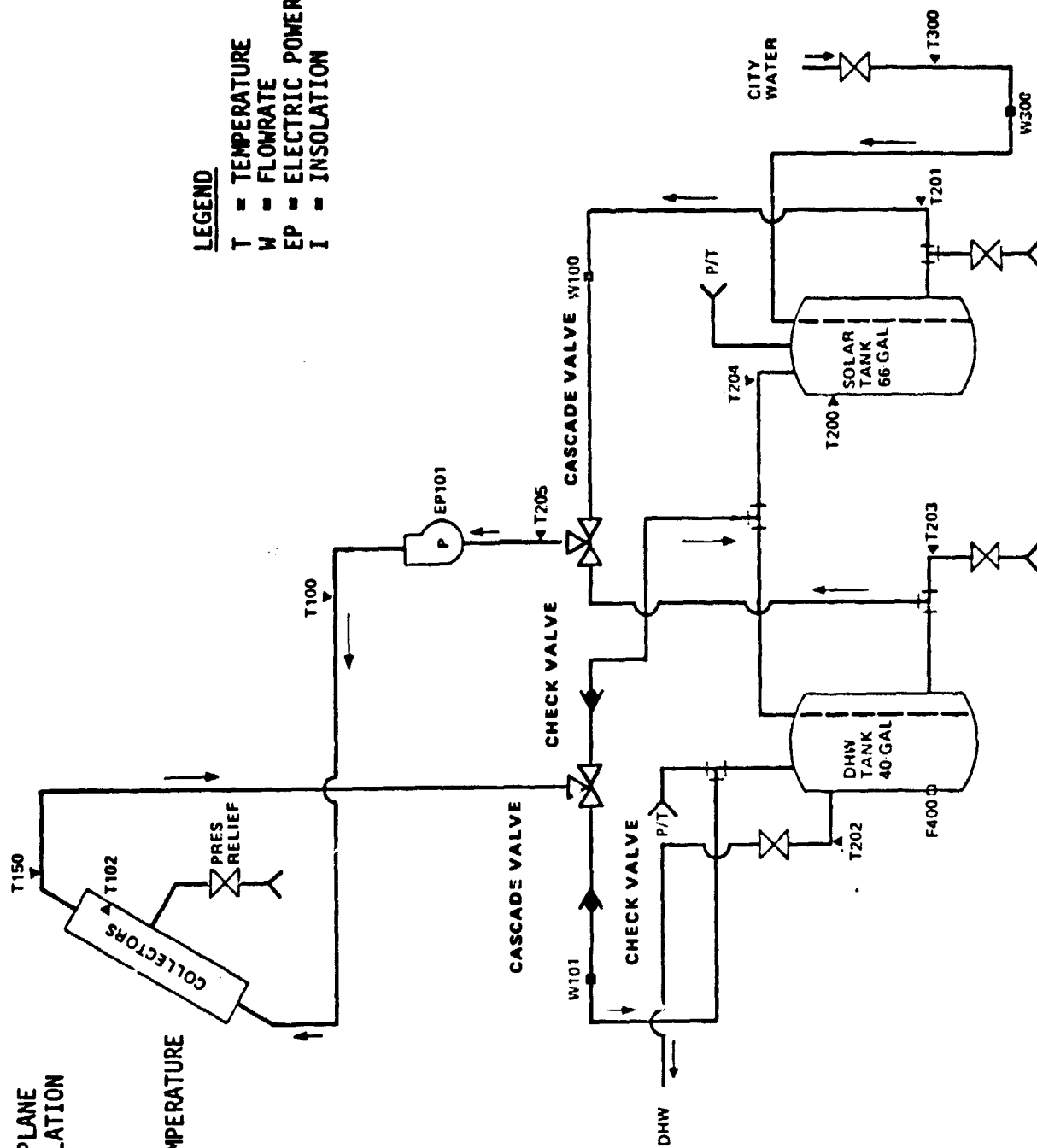
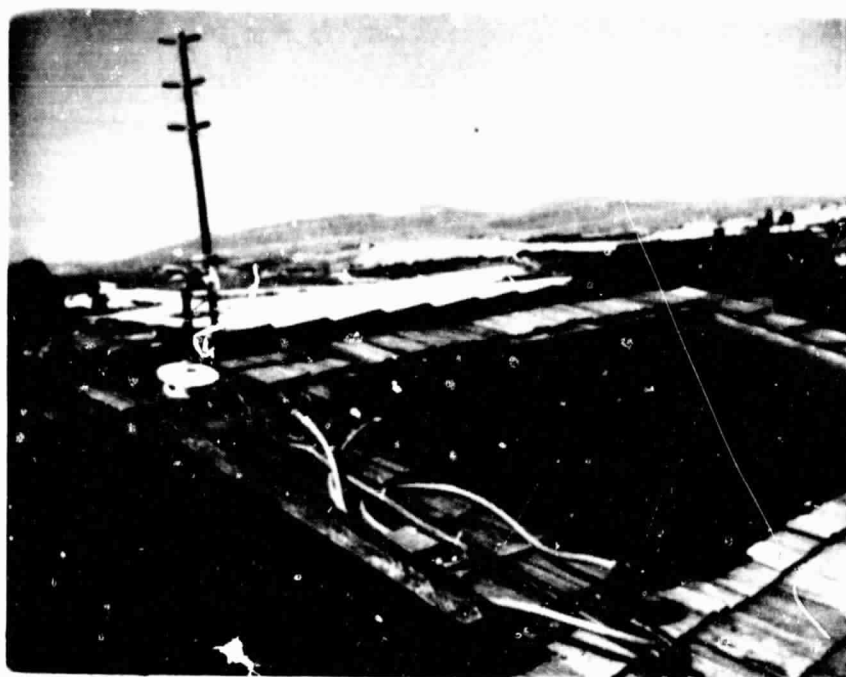


Figure 2-1 Elcam San Diego Solar Energy System Schematic



*Elcam San Diego Collector Array*

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*Elcam San Diego Site*

Figure 2-2 Elcam San Diego Pictorial

## 2.1 Typical System Operation

The auxiliary domestic hot water (DHW) heater was set at 105°F during the time the systems were monitored. This low auxiliary hot water set point allowed good utilization of solar to charge both the preheat tank and the DHW heater. The control system initiates operation when the collector outlet temperature is 20°F hotter than either the water in the bottom of the DHW tank or the preheat tank. Typically, the system would bring the DHW tank up to 140°F, and then switch the cascade valve to divert the flow to the preheat tank. At those times, such as in the mornings, when the preheat tank was cooler than the DHW tank, the water was circulated from the collectors to the preheat tank until the collector outlet temperature exceeded the DHW temperature by 20°F.

June 19, 1979 has been selected as a good day to illustrate typical operation of the Elcam San Diego site. Figure 2.1-1 (a) is a plot of solar insolation measurement, I001. System turn-on and turn-off were at 8:51 AM and 1:45 PM respectively. The 1:45 PM turn-off was because both the DHW tank and the preheat tank were fully charged. This shows that the system was functioning as designed and is typical of the operation of this site. The solar insolation was 195 Btu/ft<sup>2</sup>-hr at system turn-on and 267 Btu/ft<sup>2</sup>-hr at system turn-off.

Figure 2.1-1 (b) is a plot of the collector absorber plate temperature measurement (T102), collector inlet temperature (T100) and collector outlet temperature (T150). At the 8:51 AM system turn-on, the absorber plate temperature was 142°F, the collector inlet temperature was 117°F, and the collector outlet temperature was 130°F. At system turn-off the collector outlet temperature was 161°F and the absorber temperature 174°F. A few minutes after system turn-off, the absorber temperature reached 203°F then began to drop.

Figure 2.1-1 (c) is a plot of collector loop flow through each of the two flow meters. The W100 measurement indicates flow from the preheat tank through the collectors and measurement W101 indicates flow from the domestic hot water heaters through the collectors. For this day, the Elcam controller allowed the preheat tank to be charged first (from 8:51 AM to 11:15 AM). For the rest of the day the system cycled between the preheat tank and the domestic hot water heater.

Figure 2.1-1 (d) is a plot of the tank temperature for the day. The preheat tank was 119°F at system turn-on and 156°F at turn-off for the day. The DHW tank was 126°F at turn-on and 159°F at turn-off.

For June 19, 1979, the system operated as designed except for the thermosyphoning at night. Thermosyphoning is the natural flow process that occurs when the more dense cold water in the system gravitates toward the lowest possible point in the system, displacing the warmer water. Normally a check valve in the system prevents this thermosyphoning process, however, the check valve failed due to contaminants in the system. This will be discussed in Section 6. For this day the incident solar energy was 148,000 Btu of which 30,000 Btu was collected for a 21% collector array efficiency. The preheat tank receives 22,000 Btu with 8,000 btu going to the DHW heater.

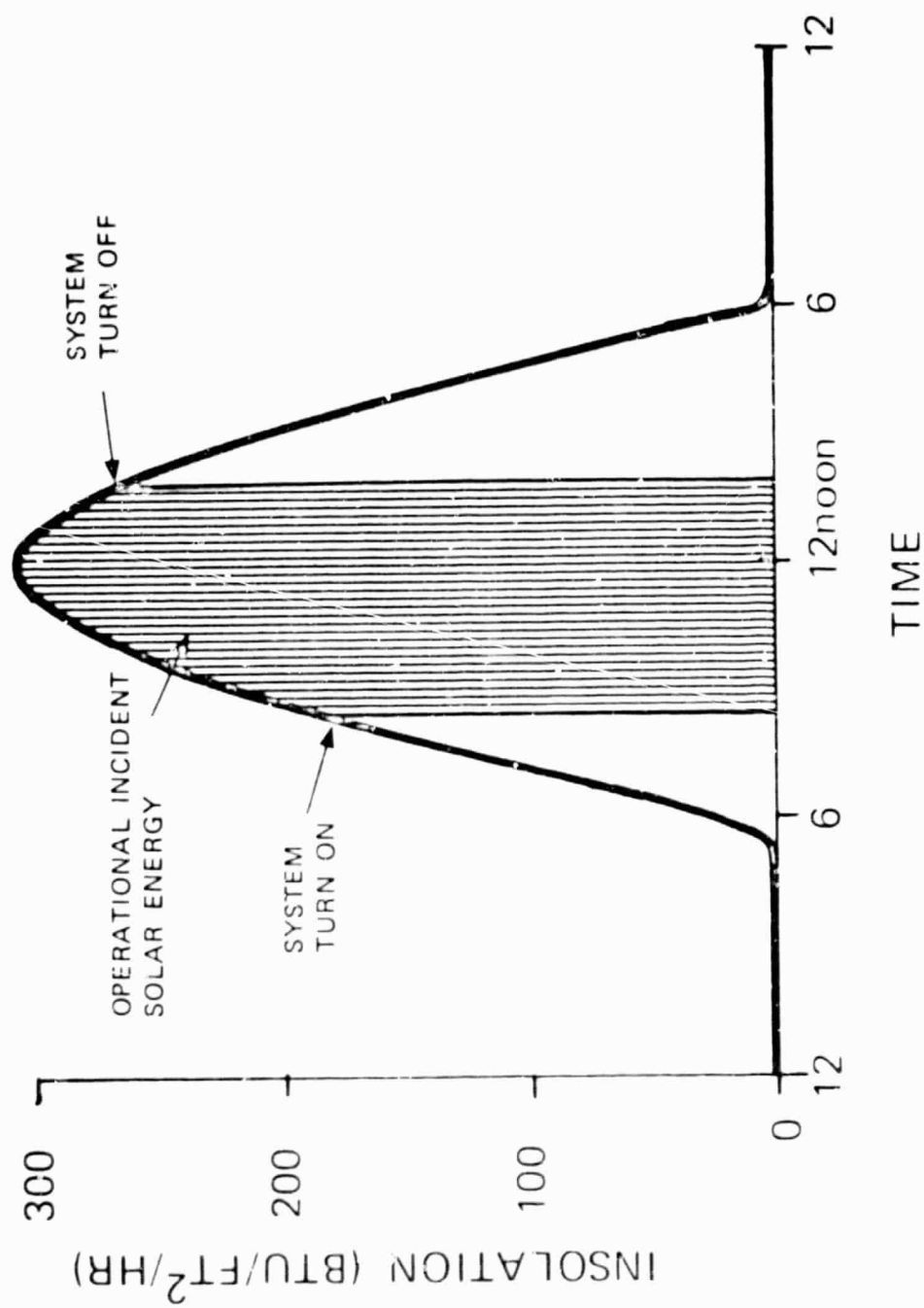
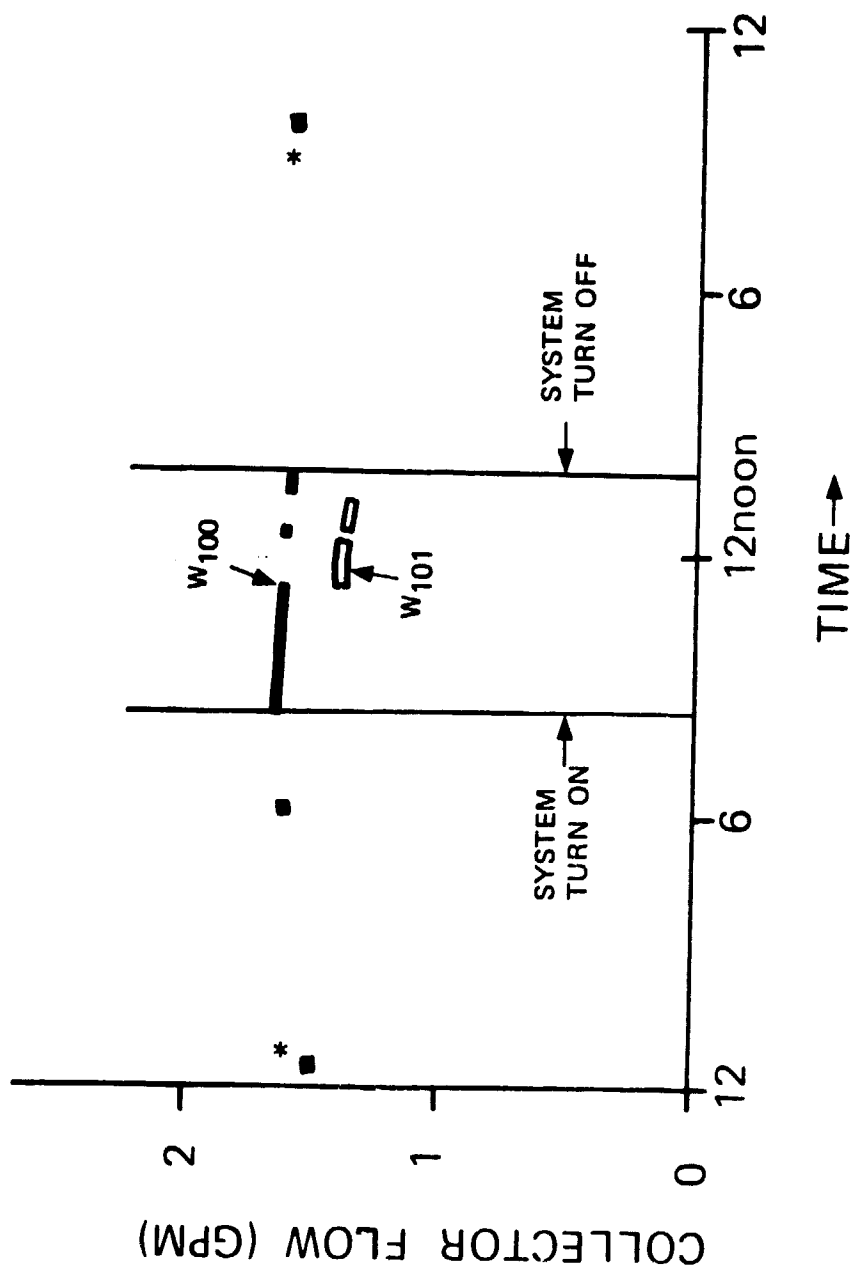


Figure 2.1-1 (a) Solar Insolation Vs. Time of Day



\* Thermosyphoning from preheat tank turned on system.

Figure 2.1-1 (c) Collector Loop Flow Vs. Time of Day

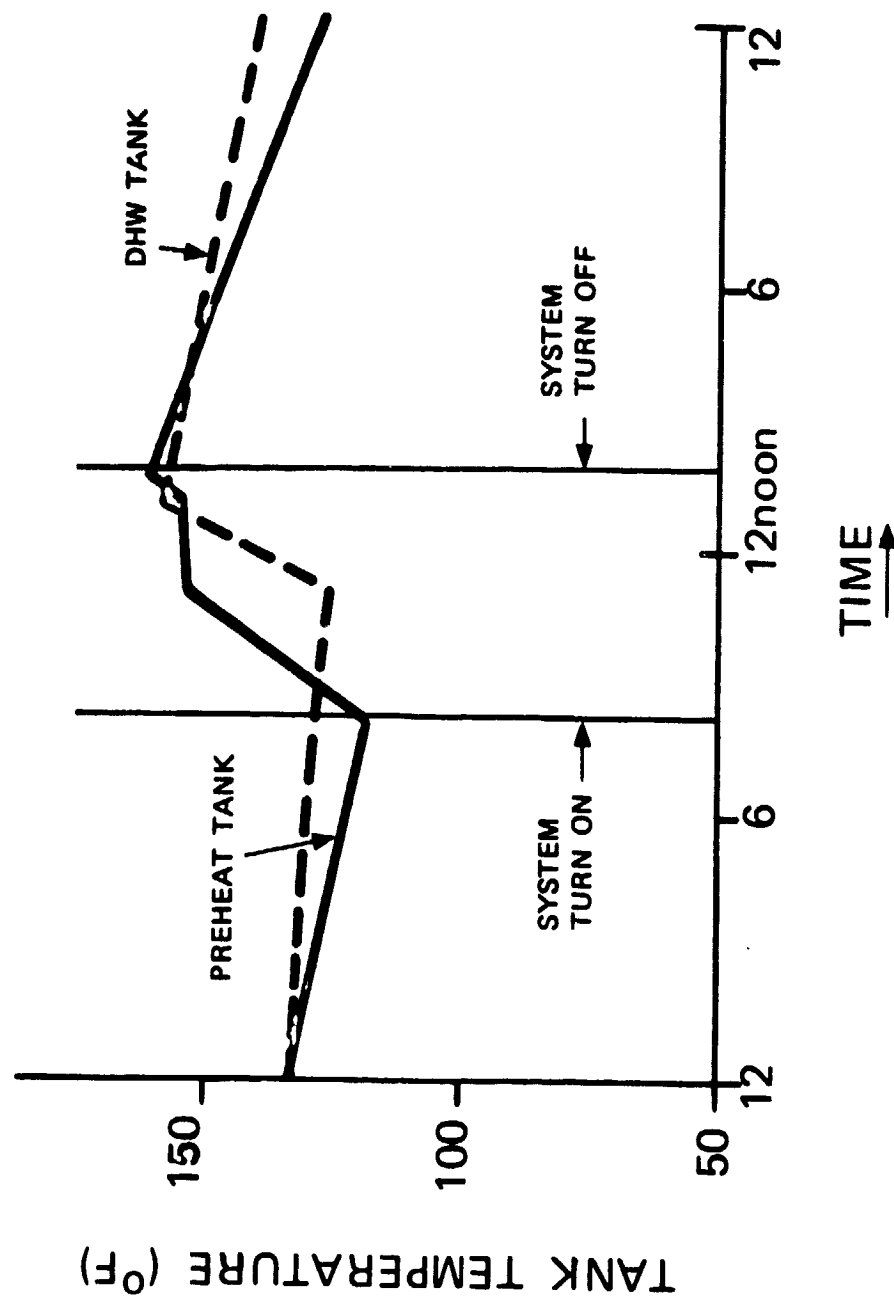


Figure 2.1-1 (d) Tank Temperature Vs. Time of Day



## 2.2 System Operating Sequence

Figure 2.2-1 shows the operating sequence of the Eicam San Diego system for June 19, 1979. The system cycled on and off once about 8:25 AM, and then turned on again at 8:51 AM. Since the DHW tank was 129°F the controller allowed the preheat tank to be charged first. At 11:15 AM the preheat tank was at 151°F and the controller switched the cascade valve to allow charging the DHW tank. By 12:08 PM the DHW tank had been charged to 150°F and the cascade valve switched back to the preheat tank. By 12:35 PM the preheat tank was up to 156°F and the cascade valve switched back to the DHW tank. By 1:12 PM the DHW tank water was above 159°F. The system turned off at 1:12 PM and cycled on and off three times for short durations, eventually bringing the preheat tank up to 166°F.

For this day the system turned off with the cascade valve set to the preheat tank and the thermosyphoning check valve stuck open. (This check valve was repaired in September 1979). As the temperature outside dropped below 60°F the system started to thermosyphon backwards from the preheat tank through the collectors. No hot water was used from 11:00 PM to 6:00 AM the next morning. During this 7 hours the preheat tank dropped 21°F, losing almost half the energy put into the tank during the day through the nighttime thermosyphoning process.



### 3. PERFORMANCE ASSESSMENT

The performance of the Elcam San Diego Solar Energy System has been evaluated for the March, 1979, 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 Elcam San Diego Solar Energy System located in San Diego, California. This analysis was conducted by evaluation of measured system performance against the expected performance with long-term average climatic conditions. The performance of the system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report, "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. The performance of the major subsystem is also evaluated in subsequent sections of this report.

The measurement data were collected for March, 1979, through September, 1979. System performance data were provided through an IBM developed Central Data Processing System (CDPS) [2] 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 monthly into formats which form a basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data given in this report.

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

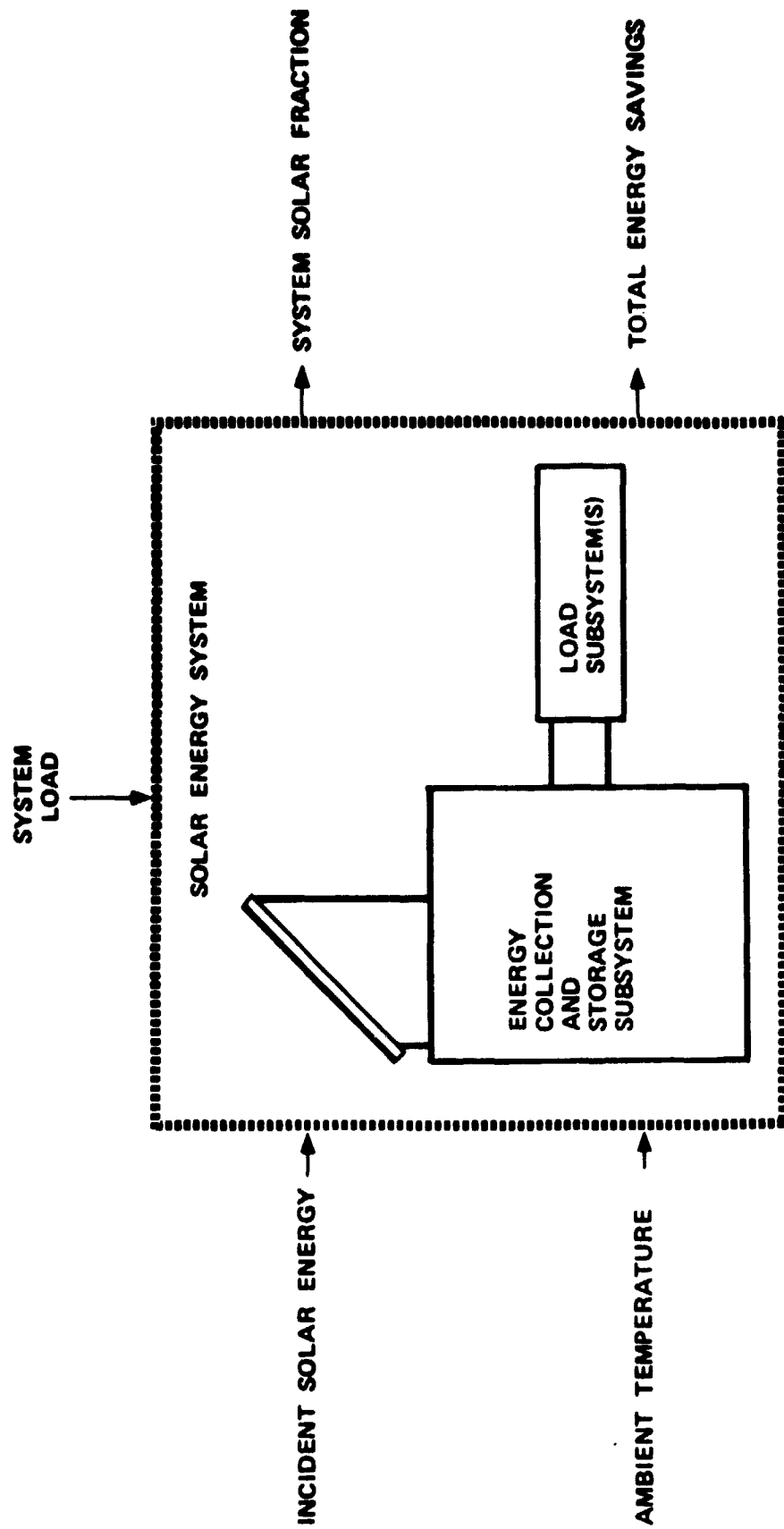


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

### Inputs

- Incident Solar Energy - The total solar energy incident on the collector array and available for collection.
- Ambient Temperature - The temperature of the external environment which affects both the energy that can be collected and the energy demand.
- System Load - The loads that the system is designed to meet, which are affected by the life style of the user (e.g., space heating/cooling, domestic hot water).

### Outputs

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

## ELCAM SAN DIEGO

| Month   | Daily Incident Solar Energy per Unit Area @18.5°Tilt (Btu/ft <sup>2</sup> ·Day) |                   | Ambient Temperature (°F) |                   | System Load (Million Btu) | Solar Fraction (Percent) |          | Energy Savings (Million Btu) |
|---------|---|-------------------|--------------------------|-------------------|---------------------------|--------------------------|----------|------------------------------|
|         | Measured  | Long Term Average | Measured                 | Long Term Average |                           | Measured                 | Expected |                              |
| Mar 79  | 1695  | 1836              | 56                       | 58                | 1.381                     | 45                       | 36       | 1.332                        |
| Apr 79  | 2049  | 1998              | 59                       | 61                | 1.242                     | 57                       | 50       | 1.388                        |
| May 79  | 1711  | 1944              | 62                       | 63                | 0.579                     | 51                       | 42       | 0.705                        |
| Jun 79  | 1825  | 1951              | 67                       | 66                | 0.391                     | 68                       | 53       | 0.640                        |
| Jul 79  | 1983  | 2091              | 68                       | 70                | 0.472                     | 74                       | 61       | 0.736                        |
| Aug 79  | 1797  | 2068              | 70                       | 71                | 0.811                     | 75                       | 51       | 1.087                        |
| Sep 79  | 1894  | 1863              | 72                       | 70                | 0.981                     | 59                       | 51       | 1.294                        |
| Total   | -   | -                 | -                        | -                 | 5.857                     | -                        | -        | 7.182                        |
| Average | 1851  | 1964              | 65                       | 66                | 0.837                     | 59*                      | 49       | 1.026                        |

\*Average value of measured solar fraction is weighted by system load.

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.

At the Elcam San Diego site for the seven month report period, the long-term average daily incident solar energy in the plane of the collector was 1964 Btu/ft<sup>2</sup>. The average daily measured value was 1851 Btu/ft<sup>2</sup> which is about 6 percent below the long-term value. On a long-term basis the good and bad months average out so that the long-term average performance should not be adversely influenced by small differences between measured and long-term average incident solar energy.

The outdoor ambient temperature influences the operation of the solar energy system in two important ways. First the operating point of the collectors and consequently the collector efficiency or energy gain is determined by the difference in the outdoor ambient temperature and the collector inlet temperature. This will be discussed in greater detail in Section 3.2.1. Secondly the load is influenced by the outdoor ambient temperature. The measured average daily ambient temperature was 65°F for the Elcam San Diego site which compares very favorably with the long-term value of 66°F.

The system load was expected to vary in a manner roughly in inverse proportion to the average monthly ambient temperature, other factors remaining constant. For the 7 month report period, the system load fluctuated from less than half of the design load in June to full design load in September. From the data in Table 3.1-1 it can be seen that the system performed very well providing 45 to 75 percent of the hot water energy.

The system load has an important affect on the system solar fraction and the total energy savings. If the load is small and sufficient energy is available from the collectors, the system solar fraction can be expected to be large. However, the total energy savings will be less than under



more normal load conditions. This is illustrated by comparing June, 1979, with March, 1979. In June the solar contribution was 68 percent with a hot water load of only 0.39 million Btu and a total net saving of 0.64 million Btu. In March the solar contribution was only 45 percent with a hot water load of 1.38 million Btu and a total net savings of 1.33 million Btu.

In a two tank domestic hot water system such as Elcam San Diego, the system load may be less than the total net energy savings. The explanation to this apparent anomaly is that solar energy was delivered to contribute to standby energy that was lost from the hot water tank. For the total report period, the system load was 5.857 million Btu, but the total net savings in energy were 7.182 million Btu.

Also presented in Table 3.1-1 are the measured and expected values of system solar fraction where system solar fraction is the ratio of solar energy applied to system load to the total thermal energy (solar plus auxiliary) applied to the load. The expected values have been derived from a modified f-Chart analysis which uses measured weather and subsystem load as inputs (f-Chart is the designation of a procedure that was developed by the Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin, for modeling and designing solar energy system [7]). The model used in the analysis is based on manufacturers' data and other known system parameters. The basis for the model is empirical correlations developed for liquid and air solar energy systems that are presented in graphical and equation form and referred to as the f-Charts where 'f' is a designator for the system solar fraction. The output of the f-Chart procedure is the expected system solar fraction. The measured value of system solar fraction was computed from measurements obtained through the instrumentation system of the energy transfers that took place within the solar energy system. These represent the actual performance of the system installed at the site.

The measured value of system solar fraction can generally be compared with the expected value so long as the assumptions which are implicit in the f-Chart procedure reasonably apply to the system being analyzed. From Table 3.1-1 the average measured value of 59 percent solar fraction exceeds the average expected value by 10 percent. There were two factors that contributed to this performance:

- Light domestic hot water load for the summer months.
- Two tank cascade configuration permitted some standby losses to be made up by solar energy.

The two tank cascade domestic hot water system at the site permitted the standby losses from the DHW tank to be made up by solar energy and is appropriate for residential DHW applications. The expected performance from the f-Chart model is predicated on a two tank system where the standby losses are assumed to be negligible, and where auxiliary energy boosts the solar contribution rather than switching to 100 percent auxiliary when the preheat tank reached some minimum set temperature.

The total energy saving is the most important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with less expensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment for the system. In terms of the technical analysis presented in this report the net total energy savings should be a significant positive figure. The total energy savings for the Elcam San Diego solar energy system was 7.18 million Btu or 2104 kWh which was less than the system's performance potential due to the light loads. Much of the energy consumed by the system went to make up standby losses.

The system performance was adversely affected by the light hot water load and two minor hardware problems during the performance period. If the load had been maintained at a value close to the design load the total net savings should have approached or even exceeded 10 million Btu (1.7 barrels of oil). The hardware problems that adversely impacted system performance were both due to mineral deposits from the supply water. The cascade valve that directs flow to the DHW tank or the preheat tank stuck in the position to direct flow to the preheat tank. The check valve, intended to prevent thermosyphoning, failed and permitted energy stored during the day to be lost through thermosyphoning at night.

### **3.2 Subsystem Performance**

The Elcam San Diego Solar Energy Installation may be divided into three subsystems:

1. Collector array
2. Storage
3. Hot Water

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

### 3.2.1 Collector Array Subsystem

The Elcam San Diego collector array consists of two Elcam flat plate liquid collectors having a gross area of 65 square feet and interconnected for parallel flow. 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:

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

where  $\eta_c$  = 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.

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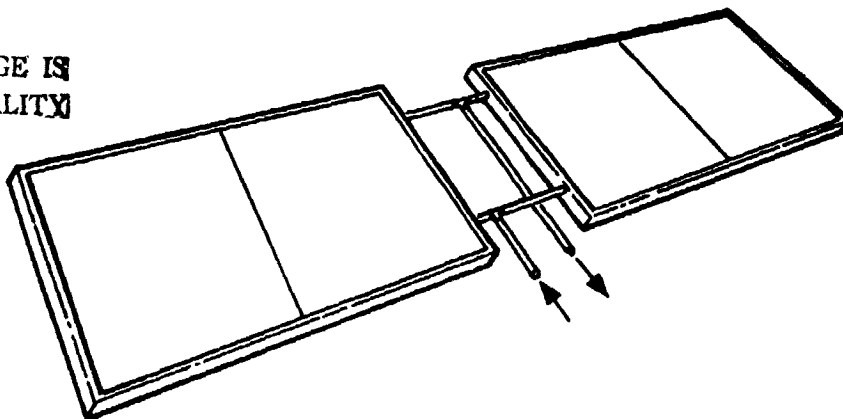


Figure 3.2.1-1(a) Collector Array Arrangement (2 Single Panels)

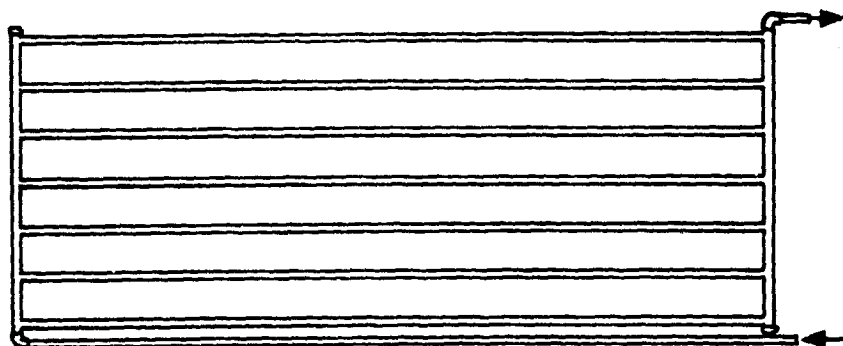


Figure 3.2.1-1(b) Collector Panel Liquid Flow Path

Collector Data

Manufacturer - Elcam, Inc.  
Type - Liquid  
Number of Collectors - Two  
Flow Path - Eight  
Flow Rate - 2 GPM  
Cover - Single 1/8 inch tempered glass

Site Data

Location - Encinitos, California  
Latitude - 32.7°N  
Collector Tilt - 18.5  
Longitude - 117.2°W  
Azimuth - 15° West of South

Figure 3.2.1-1 Collector Array Schematic

TABLE 3.2.1-1  
COLLECTOR ARRAY PERFORMANCE

| Month   | Incident Solar Energy (Million Btu) | Collected Solar Energy (Million Btu) | Collector Array Efficiency | Operational Incident Energy (Million Btu) | Operational Collector Efficiency |
|---------|-------------------------------------|--------------------------------------|----------------------------|---|----------------------------------|
| Mar 79  | 3.403                               | 1.127                                | 0.331                      | 2.582                                     | 0.436                            |
| Apr 79  | 3.980                               | 1.153                                | 0.290                      | 2.825                                     | 0.408                            |
| May 79  | 3.435                               | 0.880                                | 0.256                      | 2.107                                     | 0.418                            |
| Jun 79  | 3.545                               | 0.857                                | 0.242                      | 2.276                                     | 0.377                            |
| Jul 79  | 3.981                               | 1.031                                | 0.259                      | 2.697                                     | 0.382                            |
| Aug 79  | 3.608                               | 1.017                                | 0.282                      | 2.578                                     | 0.394                            |
| Sep 79  | 3.679                               | 1.126                                | 0.306                      | 2.786                                     | 0.404                            |
| Total   | 25.631                              | 7.191                                | --                         | 17.851                                    | --                               |
| Average | 3.662                               | 1.027                                | 0.281                      | 2.550                                     | 0.403                            |

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

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

where  $\eta_{co}$  = Operational collector array efficiency

$Q_s$  = Collected solar energy

$Q_{oi}$  = Operational incident solar energy

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

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

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

In the ASHRAE Standard 93-77 [4] a collector efficiency is defined in the same terminology as the operational collector array efficiency. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector array efficiency is determined from actual dynamic conditions of daily solar energy system operation in the field.



The ASHRAE Standard 93-77 definitions and methods often are adopted by collector manufacturers and independent testing laboratories in evaluating collectors. The collector evaluation performed for this seasonal report analysis uses long-term field measurements and is described in subsequent paragraphs. A laboratory data curve is not available for this model of collector, consequently the comments comparing the field data curves and the laboratory data curve are general in nature and are based on experience. When the laboratory data curve for the collector that is tested according to ASHRAE 93-77 differs from the long-term field data curve, there are two primary reasons for the 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.

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

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

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

$T_i$  = Collector inlet temperature

$T_a$  = Outdoor ambient temperature

$I$  = Rate of incident solar radiation

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

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

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

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

where  $\eta_j$  = Collector efficiency corresponding to the  $j^{\text{th}}$  instant

$b$  = Intercept on the efficiency axis

$(- )m$  = Slope

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

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

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

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

where  $\eta$  = Collector efficiency

$F_R$  = Collector heat removal factor

$\tau$  = Transmissivity of collector glazing

$\alpha$  = Absorptance of collector plate

$U_L$  = Overall collector energy loss coefficient

$T_i$  = Collector inlet fluid temperature

$T_a$  = Outdoor ambient temperature

$I$  = Rate of incident solar radiation

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

$$\begin{aligned} b &= F_{R\tau\alpha} \\ \text{and} & \\ m &= F_{R U_L} \end{aligned} \tag{6}$$

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 Marshall Space Flight Center (MSFC) data evaluations [8] shown in Figure 3.2.1-2. The MSFC curve is derived through techniques similar to those described in preceding paragraphs and is shown for reference. However, the MSFC data base is limited to a shorter period of time, which accounts for the small difference.

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

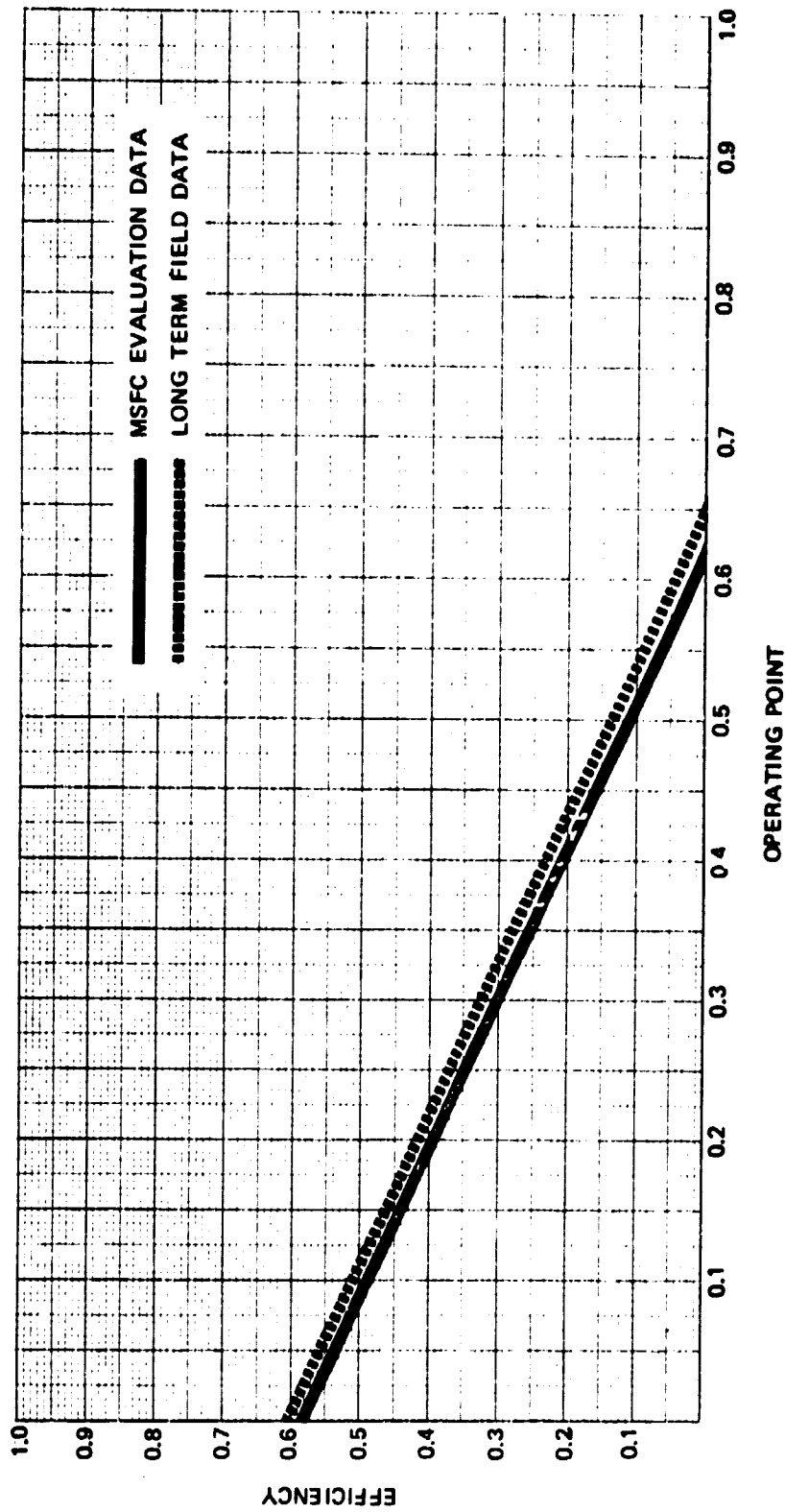


Figure 3.2.1-2 Elcam San Diego Collector Efficiency Curves

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

1. The instantaneous operating points were computed using Equation (3).
2. The instantaneous efficiency was computed using Equation (4) with the operating point computed in Step 1 above for:
  - a. The long-term linear regression curve for collector array efficiency
  - b. The laboratory single panel collector efficiency curve (when available)
3. The efficiencies computed in Steps 2a and 2b above were multiplied by the measured solar energy available when the collectors were operational to give two predicted values of solar energy collected.

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

$$\begin{aligned} \text{Error} &= (A-P)/P & (7) \\ \text{where } A &= \text{Measured solar energy collected} \\ P &= \text{Predicted solar energy collected} \end{aligned}$$

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

TABLE 3.2.1-2

## ENERGY GAIN COMPARISON

SITE: Elcam San Diego

Encinitas, California

| MONTH/YEAR | COLLECTED<br>SOLAR ENERGY<br>(MILLION BTU) | ERROR                      |                  |
|------------|--|----------------------------|------------------|
|            |  | FIELD DERIVED<br>LONG-TERM | LAB<br>PANEL     |
| Mar 79     | 1.108                                      | 0.155                      | NOT<br>AVAILABLE |
| Apr 79     | 1.215                                      | 0.193                      |                  |
| May 79     | 0.907                                      | 0.261                      |                  |
| Jun 79     | 0.868                                      | 0.223                      |                  |
| Jul 79     | 1.061                                      | 0.198                      |                  |
| Aug 79     | 1.083                                      | 0.191                      |                  |
| Sep 79     | 1.142                                      | 0.119                      |                  |
| Average    | 1.055                                      | 0.188                      |                  |

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 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 Elcam San Diego 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 18.8 percent.

The histogram of collector array operating points for September, shown in Figure 3.2.1-3, 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 continuous 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.



ELCAM - SAN DIEGO                      SAN DIEGO, CA  
 COLLECTOR TYPE: ELCAM, INC              COLLECTOR MODEL:

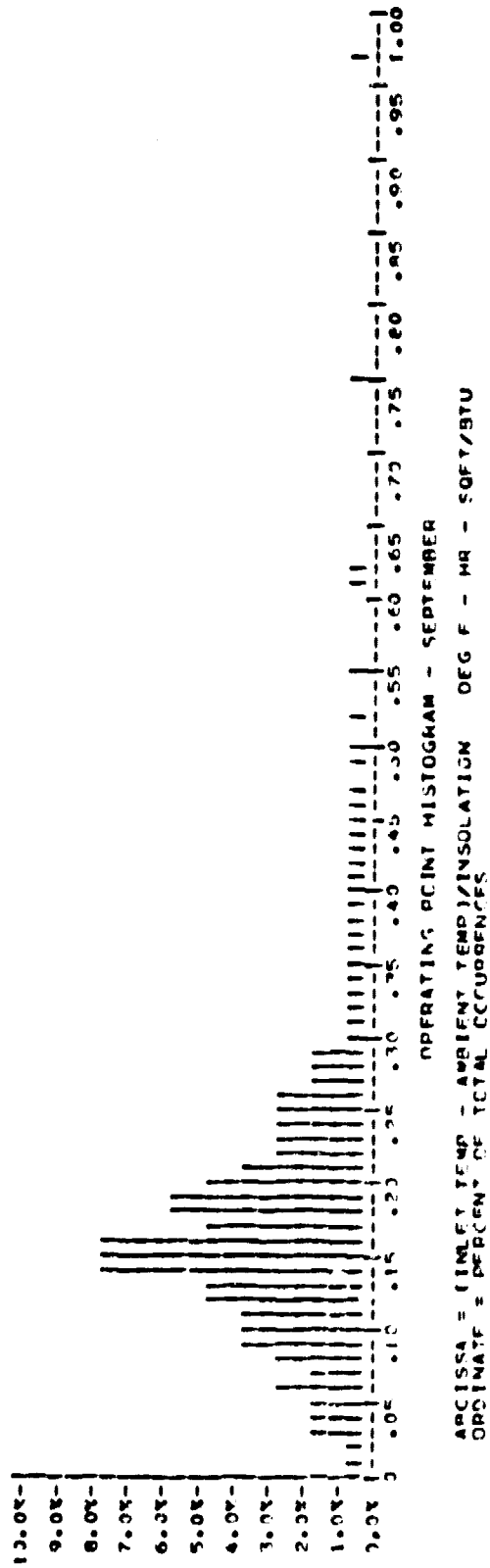


Figure 3.2.1-3 Elcam San Diego Operating Point Histogram

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Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the 7 month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equation (1) and (2).

Additional information concerning collector array analysis in general may be found in Reference [6]. The material in the reference describes the detailed collector array analysis procedures and presents the results of analyses performed on numerous collector array installations across the United States.

### 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,  $\eta_s$ . This relationship is expressed in the equation

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

where:

$\Delta Q$  = Change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

$Q_{so}$  = Energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium.

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

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

Table 3.2.2-1 summarizes energy supplied to storage and taken from storage during the reporting period. The average storage efficiency over this period was 61 percent. This high value of storage efficiency is attributed to good utilization of the solar energy. This means that the energy put into storage contributed mainly to the load instead of being dissipated in standby losses.

TABLE 3.2.2-1  
STORAGE SUBSYSTEM PERFORMANCE

| Month/Year | Energy To<br>Storage<br>(Million Btu) | Energy From<br>Storage<br>(Million Btu) | Change In<br>Stored<br>Energy<br>(Million Btu) | Storage<br>Efficiency | Storage<br>Average<br>Temperature<br>(°F) |
|------------|---------------------------------------|---|--|-----------------------|---|
| Mar 79     | 1.127                                 | 0.840                                   | -0.007   | 0.740                 | 97  |
| Apr 79     | 1.144                                 | 0.864                                   | 0.010  | 0.763                 | 107                                       |
| May 79     | 0.846                                 | 0.422                                   | -0.003   | 0.495                 | 111                                       |
| Jun 79     | 0.758                                 | 0.320                                   | -0.043   | 0.365                 | 116                                       |
| Jul 79     | 0.965                                 | 0.415                                   | -0.001   | 0.429                 | 118                                       |
| Aug 79     | 1.016                                 | 0.688                                   | 0.054  | 0.731                 | 112                                       |
| Sep 79     | 1.091                                 | 0.782                                   | 0.057  | 0.769                 | 112                                       |
| Total      | 6.947                                 | 4.331                                   | 0.067  | --                    | 773                                       |
| Average    | 0.992                                 | 0.619                                   | 0.010  | 0.613                 | 110                                       |

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### 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 Elcam San Diego Hot Water Subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in Table 3.2.3-1 is the gross energy supplied to the auxiliary system. The value of auxiliary energy supplied multiplied by the auxiliary system efficiency gives the auxiliary thermal energy actually delivered to the load. The difference between the sum of auxiliary thermal energy plus solar energy and the hot water load is equal to the thermal (standby) losses from the hot water subsystem.

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

For the 7 month period from March, 1979, through September, 1979, the solar energy system supplied a total of 4.576 million Btu to the hot water subsystem. The total hot water load for this period was 5.857 million Btu, and the weighted average monthly solar fraction was 61 percent.

The monthly average hot water load during the reporting period was 0.837 million Btu which is based on an average daily consumption of 53 gallons, delivered at an average temperature of 138°F and supplied to the system at an average temperature of 74°F.

For each month an average of 0.654 million Btu of solar energy and 0.601 million Btu of auxiliary electrical energy were supplied to the hot water subsystem. Since the average monthly hot water load was 0.837 million Btu, an average of 0.418 million Btu was, therefore, lost from the hot water tank each month.

For the March, 1979, through September, 1979, time period the hot water load was adequate for the analysis. The final hot water temperature was maintained at a level for efficient solar usage and the solar fraction was acceptable for a system of this type.

Mineral deposits from the supply water caused two hardware problems which reduced the performance of the system. The cascade valve which directs the flow to the DHW tank or preheat tank from the collectors stuck in the position to direct flow to the preheat tank. In addition the check valve intended to prevent thermosyphoning failed and permitted energy stored during the day to be lost at night. Both these problems affected the system to some extent throughout the performance period.

TABLE 3.2.3-1  
HOT WATER SUBSYSTEM PERFORMANCE

| Month/Year | Energy Supplied (Million Btu) |                    |       | Hot Water Parameters |                                     |                   | Hot Water Standby Losses (Million Btu) | Weighted** Solar Fraction (Present) |
|------------|-------------------------------|--------------------|-------|----------------------|-------------------------------------|-------------------|--|-------------------------------------|
|            | Auxiliary                     | Auxiliary* Thermal | Solar | Total                | Average Daily Consumption (Gallons) | Supply Temp. (°F) | Load (Million Btu)                     |                                     |
| Mar 79     | 1.978                         | 1.187              | 0.840 | 2.027                | 69                                  | 63                | 1.381                                  | 45                                  |
| Apr 79     | 1.491                         | 0.895              | 0.872 | 1.767                | 70                                  | 68                | 1.242                                  | 57                                  |
| May 79     | 0.948                         | 0.569              | 0.456 | 1.025                | 35                                  | 72                | 0.579                                  | 51                                  |
| Jun 79     | 0.549                         | 0.329              | 0.420 | 0.749                | 25                                  | 75                | 0.391                                  | 68                                  |
| Jul 79     | 0.329                         | 0.197              | 0.481 | 0.678                | 32                                  | 79                | 0.472                                  | 74                                  |
| Aug 79     | 0.823                         | 0.494              | 0.690 | 1.184                | 81                                  | 80                | 0.811                                  | 75                                  |
| Sep 79     | 0.899                         | 0.539              | 0.817 | 1.356                | 76                                  | 82                | 0.981                                  | 59                                  |
| Total      | 7.017                         | 4.210              | 4.576 | 8.786                | --                                  | --                | 5.857                                  | --                                  |
| Average    | 1.002                         | 0.601              | 0.654 | 1.255                | 53                                  | 74                | 0.837                                  | 59                                  |

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

#### 4. OPERATING ENERGY

Operating energy is defined as the energy required to transport solar energy to the point of use. Total operating energy for the Elcam San Diego Solar Energy System consists only of the energy required to perform Solar Energy Collection and Storage (ECSS) operations using the collector loop pump (EP100 - Figure 2-1, System Schematic). Operating energy for the system performance evaluation period are presented in Table 4-1.

Operating energy is further defined to include electrical energy that is used to support a subsystem without affecting its thermal state. Due to the cascade design with a single pump there is no separate hot water subsystem support requiring an expenditure of operating energy. The only operating energy in the system is the operating energy for the single pump (EP100) which is allocated against ECSS and total system operating energy.

The Elcam two tank cascade design is unique in domestic hot water systems for small residential applications. The cascade design allows the replenishment of standby thermal losses with solar energy which is not possible in most two tank systems. For March, 1979, through September, 1979, the period covered by this report, a total of 0.443 million Btu of operating energy was consumed. During the report period, a total of 4.576 million Btu of solar energy (Table 3.2.1-1) was supplied to the total system load. Therefore, for every one million Btu of solar energy delivered to the load, 0.10 million Btu (29 Kwh) of electrical operating energy was expended.



TABLE 4-1  
OPERATING ENERGY

| Month/Year | ECSS<br>Operating Energy<br>(Million Btu) | Hot Water<br>Operating Energy<br>(Million Btu) | Total System<br>Operating Energy<br>(Million Btu) |
|------------|---|--|---|
| Mar 79     | 0.068                                     | 0  | 0.068   |
| Apr 79     | 0.065                                     | 0  | 0.065   |
| May 79     | 0.055                                     | 0  | 0.055   |
| Jun 79     | 0.059                                     | 0  | 0.059   |
| Jul 79     | 0.065                                     | 0  | 0.065   |
| Aug 79     | 0.063                                     | 0  | 0.063   |
| Sep 79     | 0.068                                     | 0  | 0.068   |
| Total      | 0.443                                     | 0  | 0.443   |
| Average    | 0.063                                     | 0  | 0.063   |

## 5. ENERGY SAVINGS

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution. The resulting energy savings are then adjusted to reflect the thermal conversion efficiency of the auxiliary source being supplanted by solar energy. For Elcam San Diego the auxiliary source being supplanted is a natural gas DHW heater with the commonly assumed 60 percent conversion efficiency of gas to thermal energy for such devices.

Energy savings for March, 1979, through September, 1979, are presented in Table 5-1. For this performance evaluation time period, the average hot water subsystem monthly savings were 1.089 million Btu. After the Energy Collection and Storage Subsystem (ECSS) operating energy was deducted, the average net monthly electrical savings were 1.026 million Btu, or 301 Kwh. For the overall time period covered by this report the total net savings were 7.182 million Btu or 2104 Kwh. The energy savings due to the solar system were significant.

TABLE 5-1  
ENERGY SAVINGS

| Month/Year | Total<br>Hot Water Fossil<br>(Million Btu) | ECSS<br>Operating Energy<br>(Million Btu) | Net<br>Fossil<br>(Million Btu) | Net Savings   |       |
|------------|--|---|--------------------------------|---------------|-------|
|            |  |   |                                | (Million Btu) | (Kwh) |
| Mar 79     | 1.400                                      | 0.068                                     | 1.400                          | 1.332         | 390   |
| Apr 79     | 1.453                                      | 0.065                                     | 1.453                          | 1.388         | 392   |
| May 79     | 0.760                                      | 0.055                                     | 0.760                          | 0.705         | 207   |
| Jun 79     | 0.699                                      | 0.059                                     | 0.699                          | 0.640         | 188   |
| Jul 79     | 0.801                                      | 0.065                                     | 0.801                          | 0.736         | 216   |
| Aug 79     | 1.150                                      | 0.063                                     | 1.150                          | 1.087         | 318   |
| Sep 79     | 1.362                                      | 0.068                                     | 1.362                          | 1.294         | 379   |
| Total      | 7.625                                      | 0.443                                     | 7.625                          | 7.182         | 2104  |
| Average    | 1.089                                      | 0.063                                     | 1.089                          | 1.026         | 301   |

## 6. MAINTENANCE

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

### September 1979

The cascade valve which directs flow to either the DHW tank or the preheat tank, and the check valve which prevents thermosyphoning stuck. These problems were probably due to mineral deposits from the supply water. These valves were repaired during the September site maintenance visit. In addition, the unions used on the plumbing were galvanized iron and presented a potential corrosion problem due to dissimilar metals. These unions were changed out. Valves with teflon seats may alleviate the mineral deposit problem. However, a check of the critical system components should be periodically scheduled to prevent performance degradation.

## 7. SUMMARY AND CONCLUSIONS

For the report period March, 1979, through September, 1979, the average measured daily incident solar energy in the plane of the collector was  $1851 \text{ Btu/ft}^2$  which was about 6 percent below the long-term value. The average daily outdoor ambient temperature was  $65^\circ\text{F}$  which is comparable with the long-term average of  $66^\circ\text{F}$ . Consequently, weather conditions at the site had little adverse influence on system operation.

The incident solar energy for the 7 month period totaled 25.63 million Btu. Incident solar energy while the collector loop was operating was 17.85 million Btu and collected solar energy totaled 7.19 million Btu. This gives a collector operational efficiency of 40 percent. The 30 percent difference between the incident and operational incident solar energy is an acceptable value which indicates the control system is operating in the expected manner. Collector analysis data indicates the collector is operating at the expected efficiency.

Electrical energy savings at the site were a net total value of 7.18 million Btu (2104 Kwh) after the 0.44 million Btu of operating energy required to operate the collector loop circulating pump were subtracted. The energy savings due to solar were less than the system's potential due to the light load. On an average twice as much hot water could have been used which would have had the effect of significantly increasing the system solar fraction.

Mineral deposits from the supply water caused the cascade valve and check valve in the collector loop to stick. This was the only problem noted with the Elcam San Diego site during the time this data was taken. The problem was reportedly corrected in September, 1979, but reoccurred and should be checked on occasion.

## 8. REFERENCES

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APPENDIX A  
DEFINITION OF PERFORMANCE FACTORS  
AND  
SOLAR TERMS

## APPENDIX A

### DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

#### COLLECTOR ARRAY PERFORMANCE

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

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.
- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).
- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.
- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the reported collector array efficiency.



## ENERGY COLLECTION AND STORAGE SUBSYSTEM

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

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.
- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.
- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.
- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.
- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

## STORAGE PERFORMANCE

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

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.
- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.
- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).
- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.
- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

- AUXILIARY ELECTRICAL FUEL (HWAEE) is the amount of electrical energy supplied directly to the subsystem.
- ELECTRICAL ENERGY SAVINGS (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.
- SUPPLY WATER TEMPERATURE (TSW) is the average inlet temperature of the water supplied to the subsystem.
- AVERAGE HOT WATER TEMPERATURE (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.
- HOT WATER USED (HWCSM) is the volume of water used.

## HOT WATER SUBSYSTEM

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

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.
- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.
- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.
- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to directly affect the thermal state of the subsystem.
- AUXILIARY THERMAL USED (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

## ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the Development Program. It is tabulated in this report 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 (SE) 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 (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

## **APPENDIX B**

### **SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS**

## APPENDIX B

### SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR ELCAM SAN DIEGO

#### 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

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

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

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

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

where M100 is the mass flow rate of the heat transfer fluid in  $\text{lb}_m/\text{min}$  and  $\Delta H$  is the enthalpy change, in  $\text{Btu}/\text{lb}_m$ , of the fluid as it passes through the heat exchanging component.

For a liquid system  $\Delta H$  is generally given by

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

where  $\bar{C}_p$  is the average specific heat, in  $\text{Btu}/(\text{lb}_m \cdot ^\circ\text{F})$ , of the heat transfer fluid and  $\Delta T$ , in  $^\circ\text{F}$ , is the temperature differential across the heat exchanging component.

For an air system  $\Delta H$  is generally given by

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

where  $H_a(T)$  is the enthalpy, in  $\text{Btu}/\text{lb}_m$ , of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

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



For electrical power, a general example is

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

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

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

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

# EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-2

AVERAGE AMBIENT TEMPERATURE (°F)

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

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

FOR  $\pm 3$  HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT<sup>2</sup>)

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

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

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

WHEN THE COLLECTOR LOOP IS ACTIVE

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$$SECA = SEC1 + SEC2$$

$$SEC1 = \Sigma [M100 \times HRF \times (T150 - T100)] \times \Delta\tau$$

$$SEC2 = \Sigma [M101 \times HRF \times (T150 - T100)] \times \Delta\tau$$

ENTHALPY FUNCTION FOR WATER (BTU/LB)

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

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

SOLAR ENERGY TO STORAGE (BTU)

$$STEI = SEC1 = \Sigma [M100 \times HWD(T150, T100)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE (BTU)

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

AVERAGE TEMPERATURE OF STORAGE (°F)

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

ENERGY DELIVERED FROM ECSS TO LOAD (BTU)

$$CSEO = HWSE = SEC2 + SEST$$

SYSTEM OPERATING ENERGY (BTU)

$$\text{SYSOPE} = \text{CSOPE}$$

$$\text{CSEOP} = \text{EPCONST} \times \text{EP101}$$

HOT WATER CONSUMED (GALLONS)

$$\text{HWCSM} = \sum [\text{WD300}] \times \Delta \tau$$

HOT WATER LOAD (BTU)

$$\text{HWL} = \sum [\text{M300} \times \text{HWD}(\text{T202} - \text{T300})] \times \Delta \tau$$

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

$$\text{HWAEE} = \text{EPCONST} \times \text{EP300}$$

HOT WATER SUBSYSTEM AUXILIARY FOSSIL FUEL ENERGY (BTU)

$$\text{HWAFF} = \text{FCONST} \times \text{F400C}$$

SUPPLY WATER TEMPERATURE (°F)

$$\text{TSW} = \text{T300}$$

HOT WATER TEMPERATURE (°F)

$$\text{THW} = \text{T202}$$

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

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$$\text{SEA} = \text{CLAREA} \times \text{SE}$$

COLLECTED SOLAR ENERGY (BTU/FT<sup>2</sup>)

$$\text{SEC} = \text{SECA}/\text{CLAREA}$$

COLLECTOR ARRAY EFFICIENCY

$$\text{CAREF} = \text{SECA}/\text{SEA}$$

CHANGE IN STORED ENERGY (BTU)

$$\text{STECH} = \text{STECH1} - \text{STECH1}_p$$

WHERE THE SUBSCRIPT <sub>p</sub> REFERS TO A PRIOR REFERENCE VALUE

STORAGE EFFICIENCY

$$\text{STEFF} = (\text{STECH} + \text{STE0})/\text{STE1}$$

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

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

ECSS SOLAR CONVERSION EFFICIENCY

$$\text{CSCEF} = \text{SEL}/\text{SEA}$$

AUXILIARY THERMAL ENERGY TO HOT WATER SUBSYSTEM (BTU)

$$\text{HWAT} = 0.6 \times \text{HWAFF}$$

HOT WATER SOLAR FRACTION (PERCENT)

$$\text{HWSFR} = 100 \times \text{HMTKSE} / (\text{HMTKSE} + \text{HMTKAUX})$$

WHERE HMTKSE AND HMTKAUX REPRESENT THE CURRENT SOLAR  
AND AUXILIARY ENERGY CONTENT OF THE HOT WATER TANK

AUXILIARY FOSSIL FUEL (BTU)

$$\text{HAF} = \text{F400}$$

SYSTEM LOAD (BTU)

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

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

$$\text{SFR} = \text{HWSFR}$$

SYSTEM OPERATING ENERGY (BTU)

$$\text{SYSOPE} = \text{CSOPE}$$

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

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

AUXILIARY FOSSIL ENERGY TO LOADS

$$\text{AXE} = \text{HWA E}$$

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

$$\text{TSVE} = -\text{CSOPE}$$

TOTAL FOSSIL ENERGY SAVINGS (BTU)

$$\text{TSVF} = \text{HWSVF}$$

TOTAL ENERGY CONSUMED (BTU)

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

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.

ORIGINAL PAGE IS  
OF POOR QUALITY

SITE: EL CAM SAN DIEGO 100. LOCATION: SAN DIEGO CA  
ANALYST: M. STRICKLAND DRIVE NO. 78.  
COLLECTOR TILT: 18.50 (DEGREES) COLLECTOR AZIMUTH: 15.00 (DEGREES)  
LATITUDE: 32.73 (DEGREES) RUN DATES: 08/20/79

| MONTH | HOBAR | HBAR  | KBAR    | RBAR  | SRAP  | HND | CDD | TBAR |
|-------|-------|-------|---------|-------|-------|-----|-----|------|
| JAN   | 1713. | 577.  | 0.57049 | 1.329 | 1290. | 314 | 10  | 55.  |
| FEB   | 2141. | 1268. | 0.55251 | 1.227 | 1556. | 237 | 0   | 57.  |
| MAR   | 2663. | 1633. | 0.61234 | 1.124 | 1836. | 219 | 0   | 58.  |
| APR   | 3167. | 1936. | 0.61120 | 1.032 | 1998. | 144 | 15  | 61.  |
| MAY   | 3490. | 2002. | 0.57366 | 0.971 | 1944. | 79  | 26  | 63.  |
| JUN   | 3609. | 2061. | 0.57102 | 0.946 | 1951. | 52  | 67  | 66.  |
| JUL   | 3541. | 2187. | 0.61737 | 0.956 | 2091. | 6   | 149 | 70.  |
| AUG   | 3283. | 2057. | 0.62662 | 1.005 | 2069. | 0   | 201 | 71.  |
| SEP   | 2995. | 1710. | 0.60517 | 1.095 | 1963. | 16  | 163 | 70.  |
| OCT   | 2285. | 1375. | 0.60074 | 1.191 | 1639. | 43  | 77  | 66.  |
| NOV   | 1910. | 1062. | 0.58653 | 1.304 | 1384. | 140 | 14  | 61.  |
| DEC   | 1501. | 903.  | 0.56787 | 1.364 | 1232. | 257 | 0   | 57.  |

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