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# SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR IBM SYSTEM 1A, HUNTSVILLE, ALABAMA

Prepared by

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Under Contract NAS8-32036

National Aeronautics and Space Administration
George C. Marshall Space Flight Center, Alabama 35812

For the U. S. Department of Energy

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Solar Energy

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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, Sims Prototype System 1A, was designed by IBM to provide 50 to 60 percent of the space heating and domestic hot water (DHW) preheating load to a 2,000 square foot floor space single family residence in the Huntsville area. The load design temperature inside the building was to be maintained at 70 degrees fahrenheit with auxiliary energy for heating supplied by an electric heat pump assisted by an electric resistance strip heater. Auxiliary energy for domestic hot water is from a conventional 20-gallon DHW storage tank. The solar energy system, uses air as the heat transport medium, has a 720 square foot Solar Energy Products Collector Array, a 22-ton rock storage located within the office building, a pump, heat exchanger, air handler, pre-heat tank, fan and associated plumbing. The system has five different 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 in conjunction with the Final Report for each Operational Test Site in the Development Program culminates the technical activities which began with the site selection and instrumentation system design in April 1976. The Final Report emphasizes the economic analysis of solar systems performance and features the payback performance based on life cycle costs for the same solar system in various geographic regions. Other documents specifically related to this system are References [1] and [2].*

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*Numbers in brackets designate references found in Section 8.

## 2. SYSTEM DESCRIPTION

The Home Builders Association of Huntsville Office Building (Figure 2-1) located in Huntsville, Alabama, is the site selected for demonstration of the IBM System 1A. The building is constructed as a three office complex with one heating and hot water system. This system provides space heating and domestic hot water (DHW) preheating. The system, which uses air as the heat transport medium, has a 720-square foot collector array and a 22-ton rock storage located within the office building.

The system was originally designed for a single family dwelling of approximately 2,000 $ft^2$ floor space in the Huntsville area. The system was designed to supply 50 to 60% of the space heating and hot water load assuming approximately 3300 yearly heating degree days and approximately 74 gallons per day domestic hot water usage. The design temperature inside the building was to be maintained at 70°F. The design was intended to be scaled up or down to accommodate a wide range of heating and hot water requirements for other one zone single family, multi-family or small commercial buildings without significant change to the design concept.

Auxiliary energy for heating is supplied by a four-ton electric heat pump assisted by a three-stage electric resistance strip heater. Solar heating, either directly or from storage, can be assisted by a separate set of electric resistance strip heaters. Auxiliary energy for the DHW is provided by an electric resistance heating element located in the 20-gallon DHW storage tank. Figure 2-2 is a schematic of the system. The system has five different modes of operation.

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

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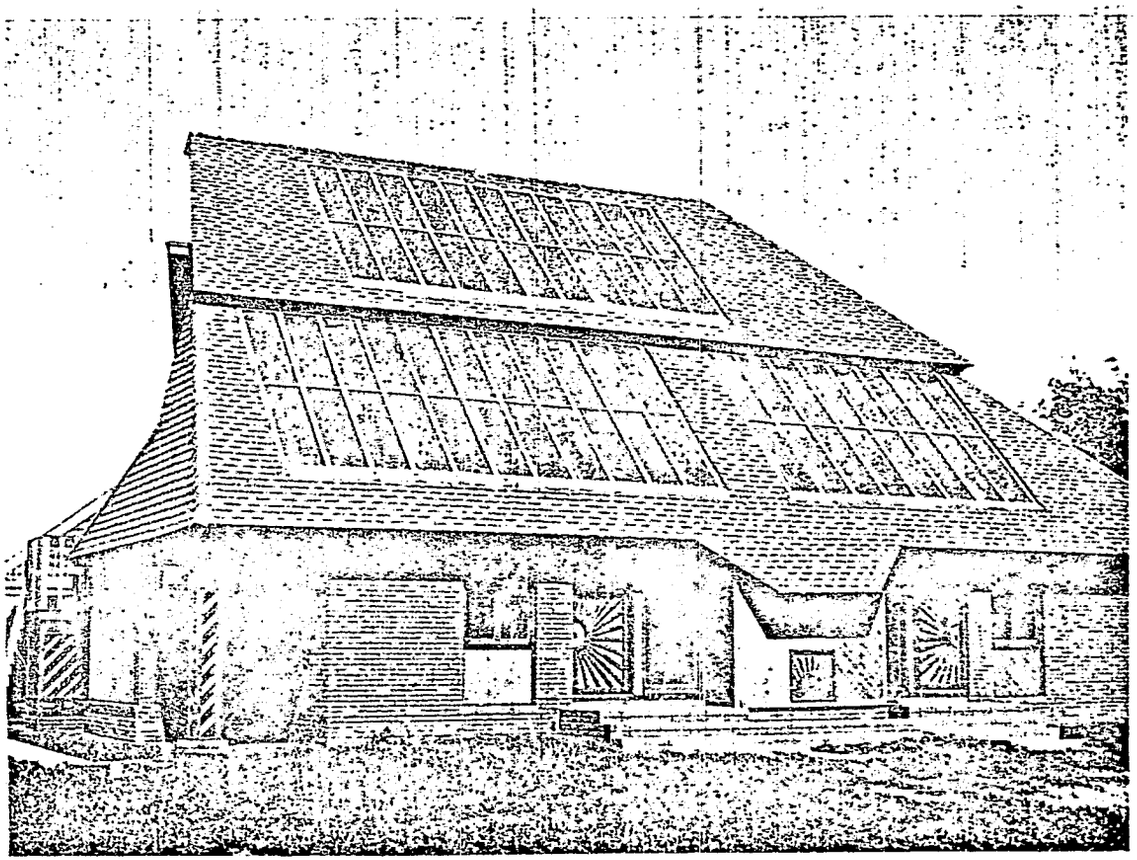

Figure 2-1 Photograph of Home Builders Association of Huntsville Office Building

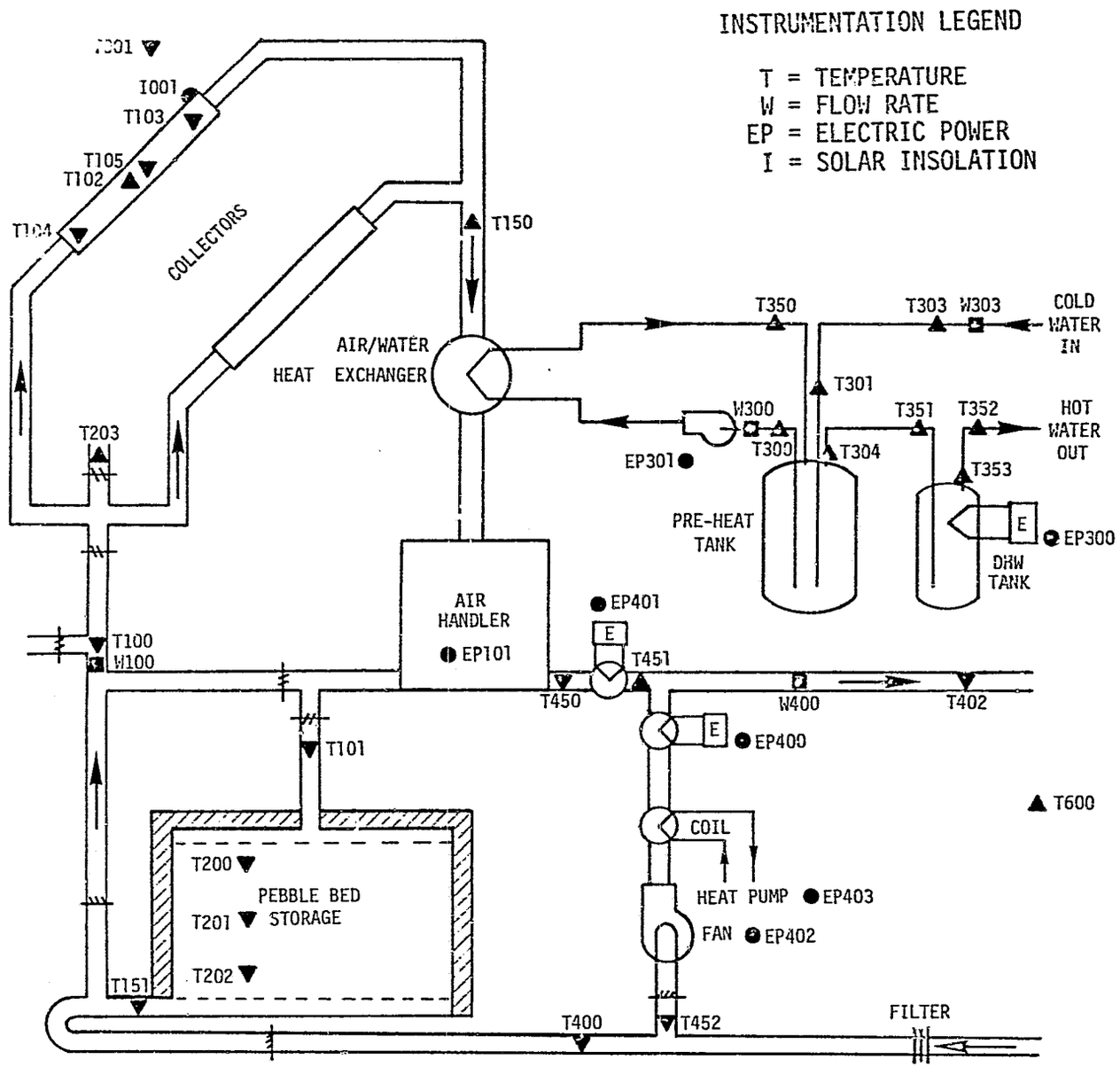


Figure 2-2 IBM System 1A Solar Energy System Schematic

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

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

Mode 4 - Collector-to-Storage: This mode exists when solar energy is available but no heat is needed in the building. When the collector outlet temperature is approximately 45°F above the bottom of rock storage, solar heated air is used to charge storage. DHW is preheated during this mode by turning on the preheat pump whenever the top of the preheat tank falls below 150°F.

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

NOTE: In Modes 1 and 2, electric strip heat auxiliary is used in series with solar heated air whenever the thermostat second stage is activated.

The collector array consists of 30 Solar Energy Products, Model EF-212 air collectors. The collectors are 2 ft. by 12 ft. rectangular units designed for integral roof (flush) mounting. The collector array is oriented due south and tilted 45° (approximately latitude +10°).

Heating storage is provided by 44,000 pounds of 3/4 inch to 1-1/2 inch washed river rock. The rock bed is located in the front of the building

between the two downstairs offices. Heat loss from three walls of the rock bed enters the building and therefore reduces the measured heating load.

The domestic hot water is preheated by circulating water from the 52 gallon preheat tank through an air to water heat exchanger in the collector outlet air duct. The conventional water heater draws its supply from the preheat tank and adds any necessary auxiliary energy.

Energy transport is provided by a Solar Control Corporation Series 20 air handler. Operation of the blower and dampers to route air flow for the various modes of system operation is achieved through the control subsystem.

The control subsystem provides for sequencing and control of the solar subsystems and heat pump auxiliary to establish operating modes suitable for all conditions of season and solar energy input. The functional units comprising the control system are: (1) Solar Control Corporation Model 75-176 controller, (2) Rho-Sigma Model 106 differential thermostat, (3) the conventional control circuit supplied with the heat pump, and (4) an interface control unit, which is a unique design for this system, to interface with the heat pump.

The solar controller is used to start and terminate collector operation in the heating season. Turn-on of the collector loop occurs when the differential temperature between the collector outlet and the bottom of the rock bed is 45°F, nominal. Collector flow is terminated when this value of differential temperature is 28°F, nominal.

The Rho-Sigma differential thermostat provides control of the domestic hot water system. Transfer of heat from the collector loop to the DHW loop starts when the differential temperature between the collector outlet and the preheat tank is 20°F, nominal and terminates when this differential falls to 5°F.

Two design changes to the control system were required after installation of the system.

The first of these changes was the addition of a delay to close appropriate motorized dampers in the air handler unit to prevent heated or cooled air from being forced back through rock storage due to occasional passive anti-backdraft damper leakage.

The second change also required the addition of a relay to the control system to prevent unwanted space heating of the building when the occupants incorrectly set the controls during a seasonal switchover.

These changes illustrate the problems that can result from interfacing a solar energy system with various types of conventional systems and the need for system design to anticipate air leakage and human operator error.

The sensor designations in Figure 2-2 are in accordance with NBS-IR-76-1137 [4]. The measurement symbol prefixes, W, T, EP and I represent respectively: flow rate, temperature, electric power and insolation.

## 2.1 Typical System Operation

Curves depicting typical system operation on a cold clear day (February 19, 1979) are presented in Figure 2.1-1. Figure 2.1-1 (a) shows the insolation (I001) on the collector array and the period when the array was operating (shaded area). On this particular day the array cycled on and off from 0806 to 0822 and then started normal operation at 0827 hours. Until approximately 1000 hours all collected solar energy was supplied to the space heating load. After 1000 hours most solar energy was put into rock storage. The array continued to operate until 1539 hours and then shut down for the day.

Figure 2.1-1 (b) shows typical collector array temperatures during the day. As the sun started to rise at approximately 0650 hours, the absorber plate temperature (T103) began to rise rapidly and reached 120°F before the system began normal operation at 0827 hours. It should be noted that temperature sensors T100, T103 and T150 are not the control sensors that govern system operation.

During the operational period the absorber plate temperature generally tracked the insolation level and collector outlet temperature (T150) showed some lag, as would be expected. Collector inlet temperature (T100) showed even more lag, since the cool rock bed storage removed most of the heat energy and returned air to the collectors at a much cooler temperature.

Figure 2.1-1 (c) shows the temperature at the top, middle and bottom of the rock bed storage. The first solar energy available from the collectors in the morning is supplied directly to load, so energy in storage does not start to increase until after 1000 hours. From 1000 hours to 1500 hours most collected solar energy is supplied to storage. The top one third of storage rises rapidly in temperature from approximately 80°F to 125°F. The center and bottom lag in temperature as is expected.

February 19, 1979 *SITE:* 004 IBM System 1A
Huntsville, AL

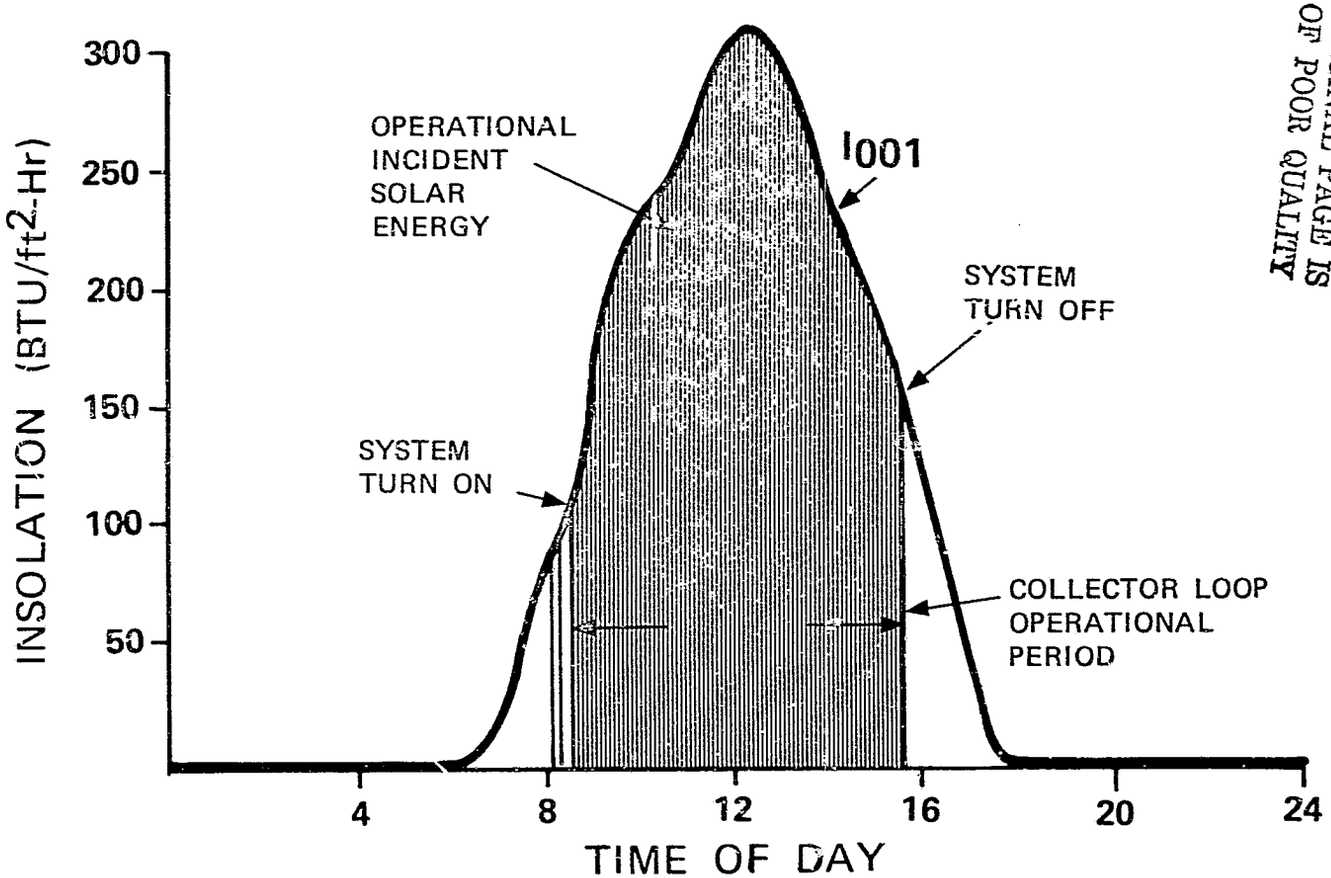


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Figure 2.1-1 (a) Solar Insolation Vs. Time of Day

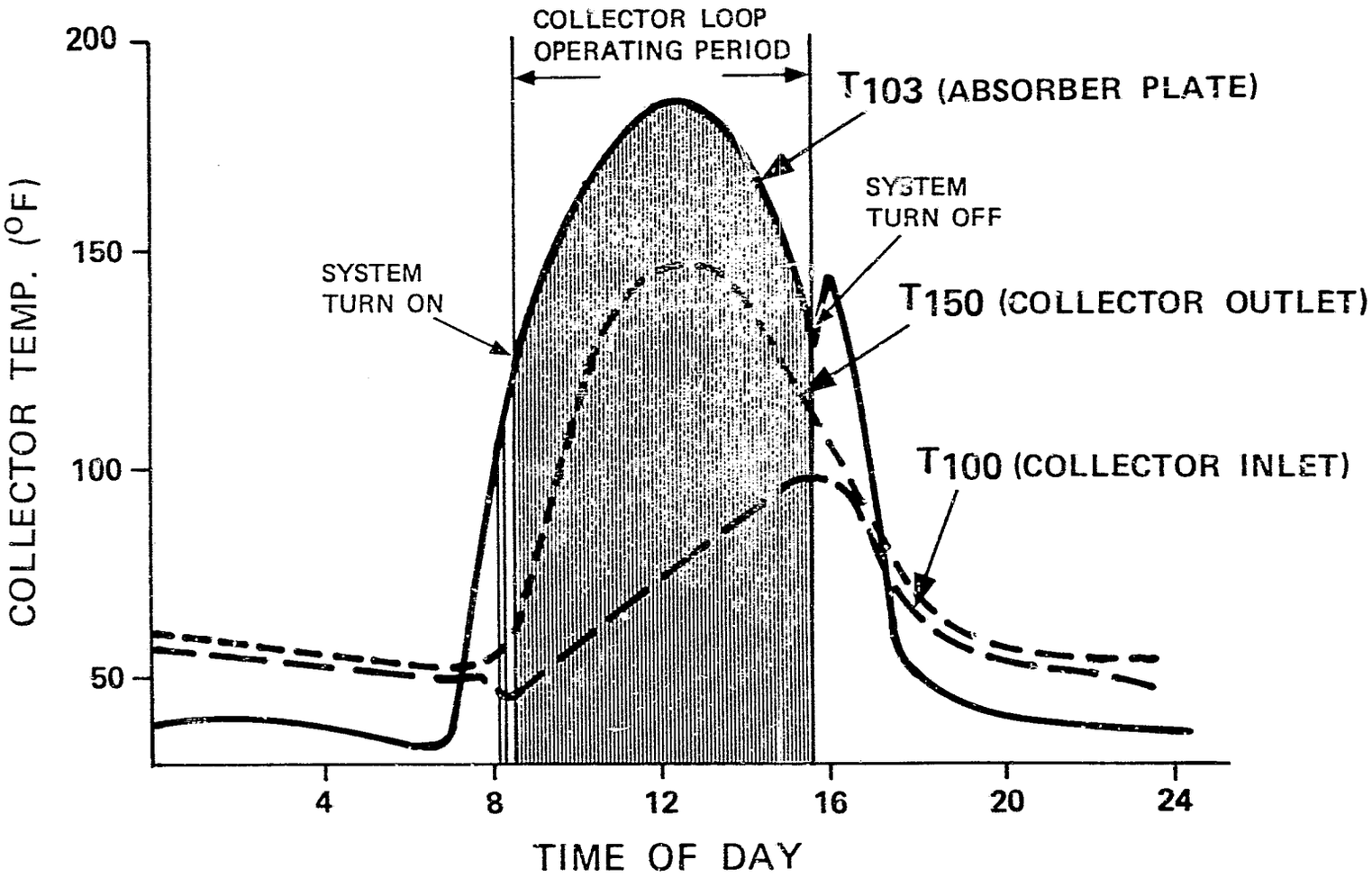


Figure 2.1-1 (b) Collector Temperatures Vs. Time of Day

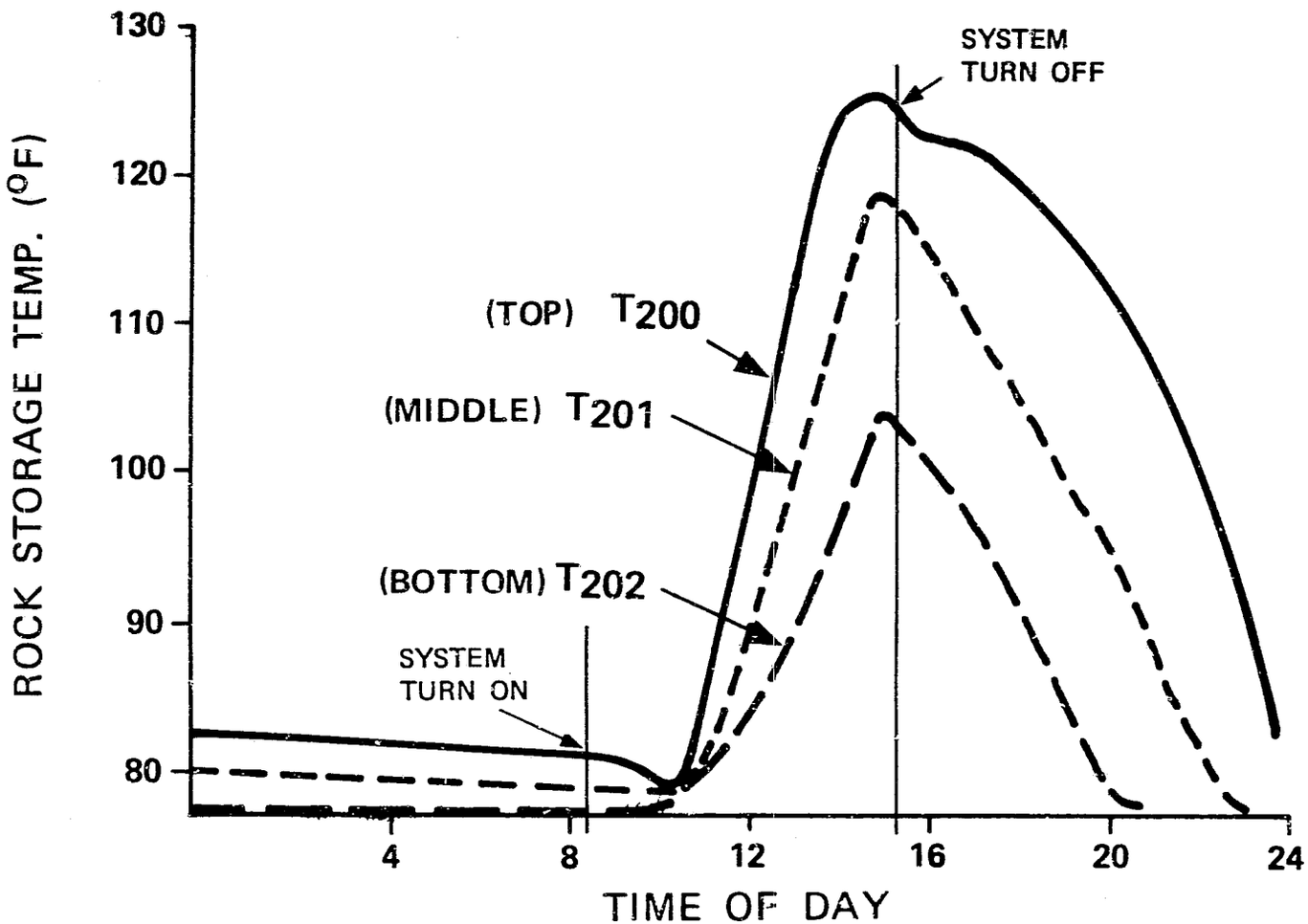


Figure 2.1-1 (c) Rock Storage Temperature Vs. Time of Day

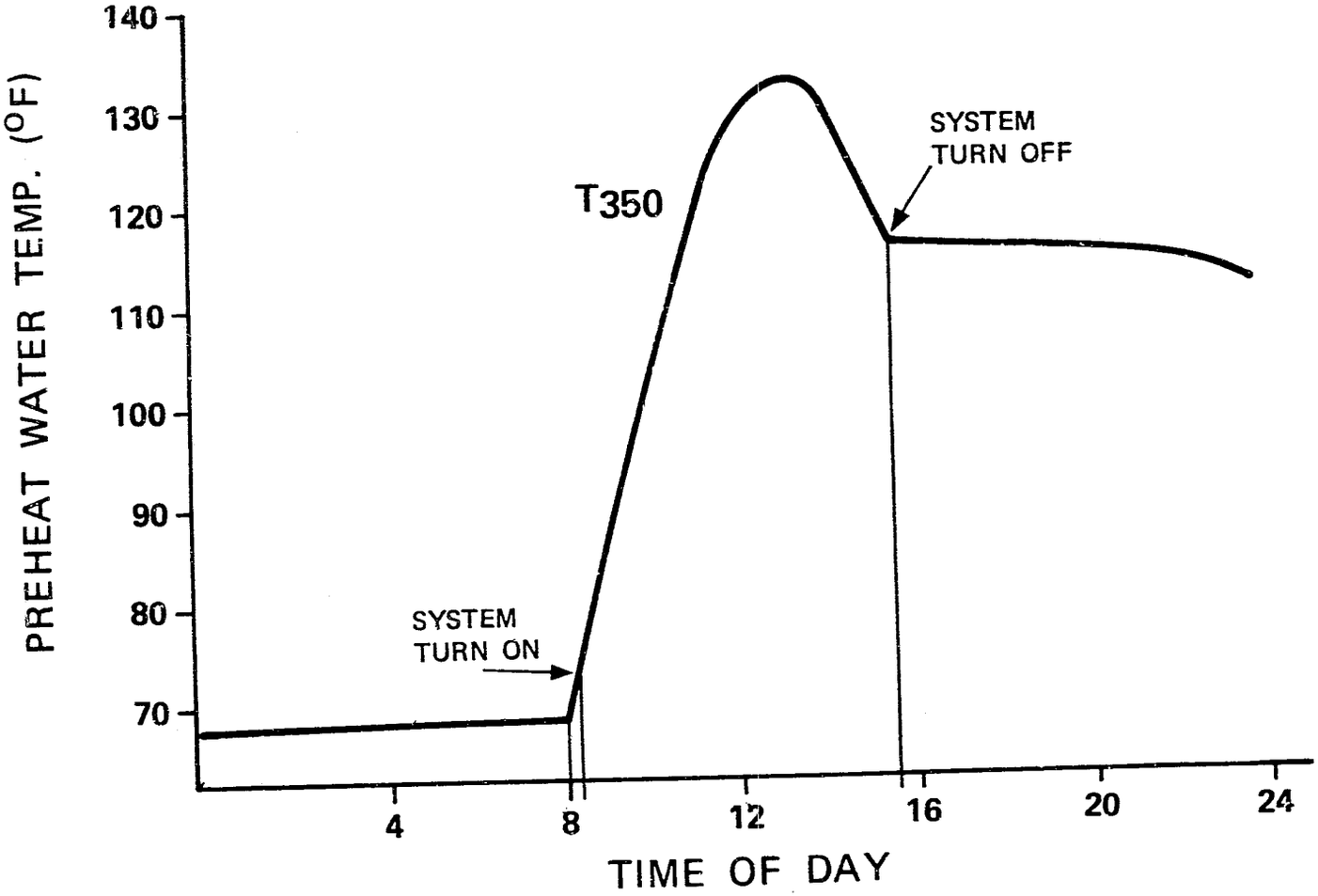


Figure 2.1-1 (d) Preheat Tank Water Temperature Vs. Time of Day

After the collector is turned off for the day, the storage temperatures start a slow decline. From approximately 1700 hours to near midnight the building heating load was supplied by storage, and the storage temperatures decline rapidly. Since the outside temperature was 25°F and the building heating load high, all of storage was depleted just before midnight. A fully charged storage was usually able to provide the necessary space heat through one night.

Figure 2.1-1 (d) is a profile of the preheated water temperature as it enters the preheat tank. During the solar collecting period the preheat tank water temperature was raised from 69°F to 120°F.

## 2.2 Typical System Operating Sequence

Figure 2.2-1 presents bar charts showing typical system operating sequences for February 19, 1979. This data correlates with the curves presented in Figure 2.1-1 and provides some additional insight into those curves.

Auxiliary space heating was required until approximately 0800 hours, at which time solar began to cycle on and attempted to meet the load. The limited cycling is indicative of proper operation of the control system; i.e., the sensitivity is adjusted to take maximum advantage of the useful solar energy that is available. From 0822 to 1003 hours all collected solar energy was supplied directly to the building. At 1003 hours the outside ambient temperature had risen to 30°F with the sun shining brightly, and the building heating load began to drop off. As the building heating load became less, a larger share of the solar energy was available to charge rock storage.

Solar energy was used all day to charge the domestic hot water preheat tank. No hot water was used on this day, so the auxiliary electric water heater cycled on and off about every 1-1/2 hours to keep the hot water at the set temperature (normal hot water heater operation). The typical hot water usage for this site was 5 to 15 gallons per day for the work days with no usage on weekends. With a solar domestic hot water preheat system, only the preheat tank is charged with solar energy. When hot water is used, solar heated water from the preheat tank is supplied to the domestic hot water heater. If no hot water is used, all the solar heated water stops in the preheat tank and all DHW tank losses must be made up with auxiliary energy. This indicates that a single tank domestic hot water system is more appropriate for light loads. In the light load applications, maximum collection of solar energy is not necessary, and tank losses can be made up with solar energy, conserving auxiliary energy.

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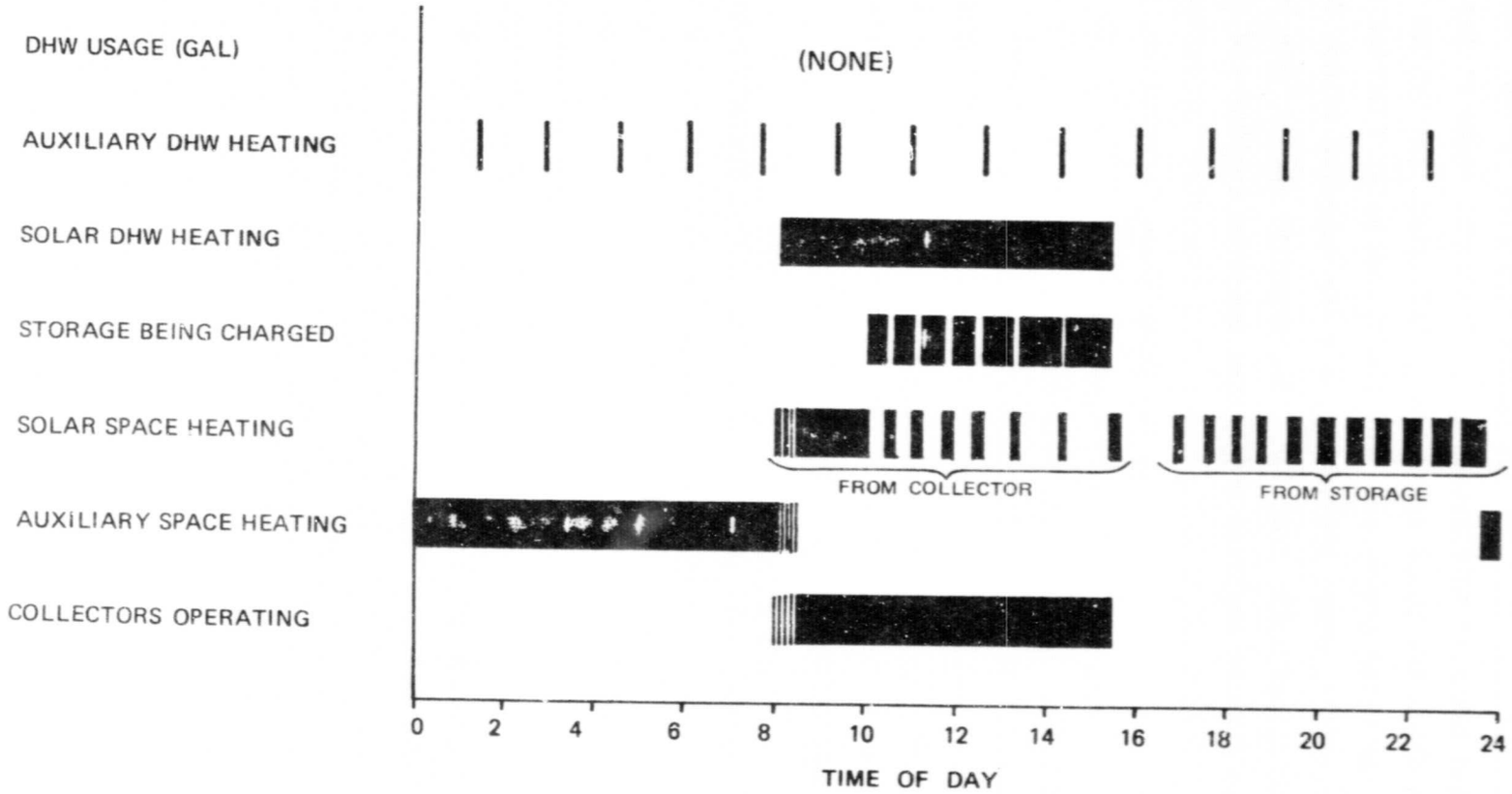


Figure 2.2-1 Typical System Operating Sequence

## 3. PERFORMANCE ASSESSMENT

The performance of the IBM System 1A Solar Energy System has been evaluated for the September 1978 through August 1979 time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load, the measured values for solar energy used and the system solar fraction have been presented. Also presented, where applicable, are the expected values for solar energy used and system solar fraction. The expected values have been derived from a modified f-Chart analysis which uses measured weather and subsystem loads as inputs (f-Chart is the designation of a procedure for designing solar heating systems that was developed by the Solar Energy Laboratory, University of Wisconsin-Madison). The model used in the analysis is based on manufacturers' data and other known system parameters. The second view presents a more in-depth look at the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the domestic hot water subsystem and the space heating subsystem. Included in this are all parameters pertinent to the operation of each individual subsystem.

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

## 3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the IBM-System 1A Solar Energy System located in Huntsville, Alabama. This analysis was conducted by evaluation of measured system performance against the expected performance with long-term average climatic conditions. The performance of the system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report, "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [4]. The performance of the major subsystems is also evaluated in subsequent sections of this report.

The measurement data were collected for the period September 1978 through August 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 formats which form a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data given in this report.

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

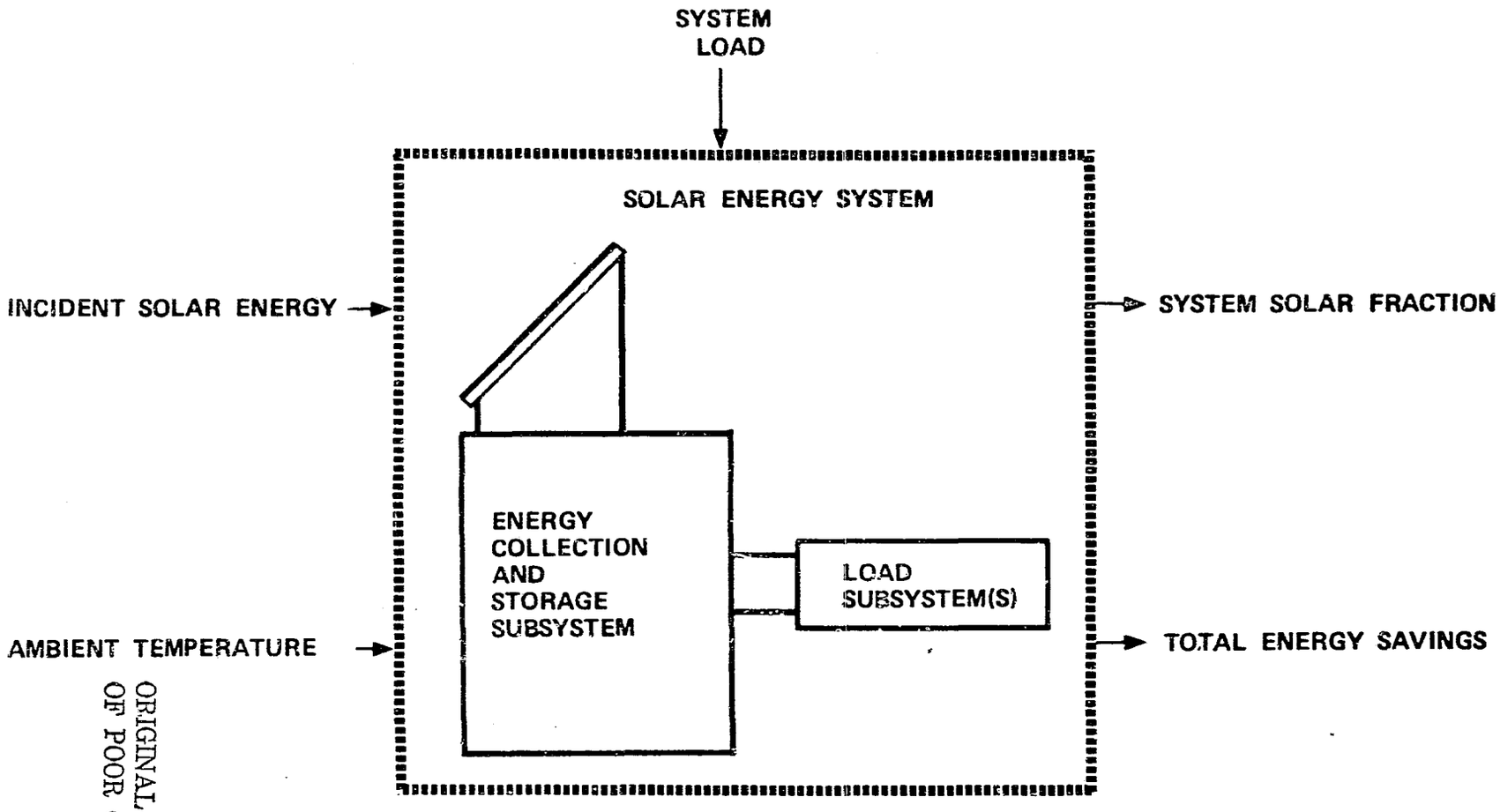


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Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

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

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

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

Outputs

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

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

The monthly values of the inputs and outputs for the total operational period are shown in Table 3.1-1, the System Performance Summary. Comparative long-term average values of daily incident solar energy, and outdoor ambient 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 solar energy and

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY

| Month | Daily Incident Solar Energy per Unit Area @ 45° Tilt (Btu/ft$^2$·Day) | | Ambient Temperature °F | | System Load-Measured (Million Btu) | Solar Fraction (Percent) | | Total Energy Savings (Million Btu) |
|---|---|---|---|---|---|---|---|---|
| | Measured | Long Term Average | Measured | Long Term Average | | Measured | Expected | |
| Sep 78 | 1,167 | 1,509 | 76 | 73 | 0.900 | 37 | 100 | -0.175 |
| Oct 78 | 1,571 | 1,510 | 60 | 62 | 0.539 | 13 | 100 | -0.220 |
| Nov 78 | 950 | 1,172 | 54 | 50 | 2.092 | 75 | 100 | 0.327 |
| Dec 78 | 942 | 912 | 45 | 42 | 10.612 | 50 | 47 | 1.984 |
| Jan 79 | 694 | 958 | 33 | 41 | 23.975 | 17 | 10 | 1.736 |
| Feb 79 | 731 | 1,179 | 40 | 44 | 17.510 | 21 | 15 | 1.563 |
| Mar 79 | 1,263 | 1,365 | 54 | 51 | 4.276 | 72 | 100 | 0.990 |
| Apr 79 | 1,225 | 1,523 | 61 | 62 | 0.814 | 38 | 100 | -0.147 |
| May 79 | 1,208 | 1,527 | 69 | 70 | 0.075 | 41 | 100 | -0.255 |
| Jun 79 | 1,375 | 1,516 | 75 | 77 | 0.165 | 79 | 100 | -0.146 |
| Jul 79 | 1,076 | 1,489 | 78 | 80 | 0.160 | 63 | 100 | -0.111 |
| Aug 79 | 1,361 | 1,553 | 78 | 79 | 0.150 | 78 | 100 | -0.100 |
| Total | 13,363 | 16,213 | — | — | 61.270 | — | — | 5.446 |
| Average | 1,130 | 1,351 | 60 | 61 | 5.11 | 31* | 35* | 0.454 |

* Averages are weighted values.

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

The measured average daily value for insolation at the IBM System 1A site for the twelve months of the reporting period was 1130 Btu/ft$^2$. In order to evaluate this measured data, a comparison with a long-term average value is usually made. There has never been a long-term measure of insolation anywhere in the immediate Huntsville area, although a monitoring effort was begun by the Johnson Environmental and Energy Center in May, 1976. This would hardly seem adequate for providing a baseline comparison, so a composite figure based on the measurements in Birmingham, Alabama, 100 miles to the south and of Nashville, Tennessee, 100 miles to the north was used. (Weighting factors of 0.5435 and 0.4565 were used for Birmingham and Nashville respectively.) The average of this composite insolation data for the report period was 1357 Btu/ft$^2$. Examining the difference month by month between the measured insolation and this long-term composite shows that with the exception of October, 1978 and January, 1979, in every case the insolation measured at the 1A site was lower. There was speculation throughout the analysis period that the insolation values recorded at 1A might be low due to a dirty pyranometer. Since there is an obvious disparity between the measured data and what has been used as the long-term average insolation, other comparisons were sought. There was one other solar site (Chester West) in Huntsville which was monitored in an identical manner as was 1A, a residence in the northwest area of the city, for which insolation data was available [10]. Also the data collected by the Johnson Energy Center, although not monitored and converted precisely the same, was available [11]. Data from both these sources have been collected and analyzed for the report period and show 1231 Btu/ft$^2$ and 1284 Btu/ft$^2$ for the NSDN site and the Johnson Solar Energy Center data respectively. Both of these values are also below the long-term composite

obtained from the mixing of Birmingham and Nashville, however, they are still larger than the values recorded at the 1A site. Table 3.1-2 shows a comparison of data from the four sources. It may then be concluded, assuming the validity of the process for computing the composite long-term average, that the insolation in Huntsville was below normal during the report period, but that the indications received at the 1A site were based still lower for some reason, probably a dirty paranometer.

The outdoor ambient temperature influences the operation of the solar energy system in two important ways. First the operating point of the collectors and consequently the collector efficiency or energy gain is determined by the difference in the outdoor ambient temperature and the collector inlet temperature. This will be discussed in greater detail in Section 3.2.1. Secondly the load is influenced by the outdoor ambient temperature. The long-term average daily ambient temperature was 61°F for the IBM System 1A site which compares very favorably with the measured value of 60°F. On a monthly basis December, January and February were the worst months temperaturewise. With the exception of January and February which were low on insolation and colder than normal, there was negligible adverse impact on system performance due to weather.

The system load was expected to vary in a manner roughly in inverse proportion to the average monthly ambient temperature, other factors remaining constant. During the twelve month reporting period, a total of 58.37 million Btu of solar energy was collected and the total system load was 61.27 million Btu. The measured amount of solar energy delivered to the load was 21.58 million Btu, which was slightly lower than the expected amount due mainly to the low hot water usage.

TABLE 3.1-2

INSOLATION DATA COMPARISON

| Month | Measured 1A Data 45° Tilt ($Btu/ft^2Day$) | Measured Chester West Data 45° Tilt ($Btu/ft^2Day$) | Measured UAH Data 45° Tilt ($Btu/ft^2Day$) | Long Term Data from Nashville/ Birmingham (f-Chart) ($Btu/ft^2Day$) |
|---|---|---|---|---|
| Sep 78 | 1167 | 1306 | 1303 | 1509 |
| Oct 78 | 1571 | 1862 | 1665 | 1510 |
| Nov 78 | 950 | 1140 | 1181 | 1172 |
| Dec 78 | 942 | 1123 | 981 | 912 |
| Jan 79 | 694 | 716 | 755 | 958 |
| Feb 79 | 731 | 862 | 917 | 1179 |
| Mar 79 | 1263 | 1369 | 1351 | 1365 |
| Apr 79 | 1225 | 1361 | 1367 | 1523 |
| May 79 | 1209 | 1147 | 1369 | 1527 |
| Jun 79 | 1375 | 1328 | 1485 | 1516 |
| Jul 79 | 1076 | 1142 | 1314 | 1489 |
| Aug 79 | 1361 | 1418 | 1725 | 1553 |
| Average | 1130 | 1231 | 1284 | 1351 |

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Also presented in Table 3.1-1 are the measured and expected values of system solar fraction where system solar fraction is the ratio of solar energy applied to system loads to the total energy (solar plus auxiliary) applied to the loads. The expected values have been derived from a modified f-Chart analysis which uses measured weather and subsystem loads as inputs (f-Chart is the designation of a procedure that was developed by the Solar Energy Laboratory, University of Wisconsin-Madison, for modeling and designing solar energy systems [8]). The model used in the analysis is based on manufacturers' data and other known system parameters. The basis for the model are empirical correlations developed for liquid and air solar energy systems that are presented in graphical and equation form and referred to as the f-Charts where 'f' is a designator for the system solar fraction. The output of the f-Chart procedure is the expected system solar fraction. This in turn is multiplied by the system load to derive the expected value of solar energy used. 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 31 percent solar fraction falls short of the average expected value by 4 percentage points. The primary reason for the actual solar fraction being slightly low is the very low domestic hot water load at the site. With very little or no hot water used each day, most of the solar energy placed in the preheat tank went to tank losses which were not counted as system load.

A single tank hot water system would have functioned better for this site. The two tank system is not appropriate for light load applications.

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 inexpensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment of the system. In terms of the technical analysis presented in this report the net total energy savings should be a significant positive figure. The total energy savings for the IBM System 1A Solar Energy System was 5.45 million Btu or 1597 KwH which was less than the system's savings potential. Operating the system during the summer for preheating hot water did not save energy. If the system had been turned off during the non-heating months, 6.60 million Btu or 1934 KwH could have been saved. If the system were used in a family dwelling, as originally designed, the hot water load would probably justify all year operation.

## 3.2 Subsystem Performance

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

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

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

### 3.2.1 Collector Array Subsystem

The IBM System 1A collector array consists of 30 Solar Energy Products, Model EF-212 flat plate air collectors having a gross area of 720 square feet. Flow details and other pertinent operational characteristics are shown in Figure 3.2.1-1. The collector subsystem analysis and data are given in the following paragraphs.

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

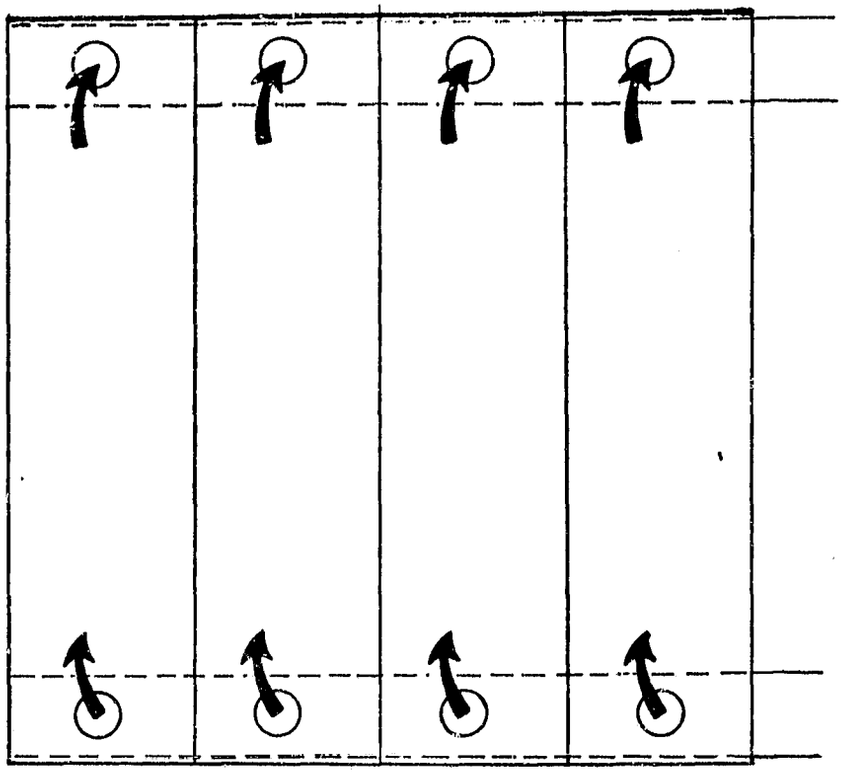
$$\eta_c = Q_s/Q_i \qquad (1)$$

where $\eta_c$ = 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.



Collector Data

Manufacturer - Solar Energy Products Co.

Model - EF212

Type - Air

Number of Collectors - 30

Flow Paths - 30 CFM - 800

Site Data

Location - Huntsville, Alabama

Latitude - 34.5° Longitude - 86.5°

Collector Tilt - 45° Azimuth - 0.0°

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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 |
|---|---|---|---|---|---|
| Sep 78 | 25.198 | 1.666 | 0.066 | 7.303 | 0.23 |
| Oct 78 | 35.070 | 4.818 | 0.137 | 12.544 | 0.38 |
| Nov 78 | 20.509(25.053)* | 5.618 | 0.274(0.224)* | 10.577(12.921)* | 0.53(0.44)* |
| Dec 78 | 21.027(23.482)* | 8.918 | 0.424(0.380)* | 15.450(17.254)* | 0.58(0.52)* |
| Jan 79 | 15.479(16.405)* | 6.405 | 0.414(0.390)* | 10.743(11.385)* | 0.60(0.56)* |
| Feb 79 | 14.742(17.938)* | 5.874 | 0.398(0.327)* | 9.597(11.678) | 0.61(0.50)* |
| Mar 79 | 28.194(30.359)* | 10.314 | 0.366(0.340)* | 20.158(21.706)* | 0.51(0.48)* |
| Apr 79 | 26.459(29.461)* | 5.562 | 0.210(0.189)* | 10.952(12.195)* | 0.51(0.46) |
| May 79 | 26.971 | 2.604 | 0.097 | 10.295 | 0.25 |
| Jun 79 | 29.709 | 2.436 | 0.082 | 10.165 | 0.24 |
| Jul 79 | 24.019 | 1.929 | 0.080 | 7.837 | 0.25 |
| Aug 79 | 30.385 | 2.227 | 0.073 | 8.974 | 0.25 |
| Total | 297.762 | 58.369 | -- | 134.595 | -- |
| Average | 24.814 | 4.864 | 0.218 | 11.216 | 0.41 |

*The values of Incident Solar Energy and Operational Incident Energy were adjusted to the average of the Chester West data and the UAH data (Table 3.1-2) to reflect the estimated error due to the dirty spot on the pyranometer. The Collector Array Efficiency and Operational Collector Efficiency were recomputed based on these estimates. The adjusted and recomputed values are shown in parentheses.

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

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

where $\eta_{co}$ = 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 [6] a collector efficiency is defined in the same terminology as the operational collector array efficiency. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector array efficiency is determined from actual dynamic conditions of daily solar energy system operation in the field.

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

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

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

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

The 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:

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

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 ($\eta_j$, $x_j$) 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.

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

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

$b$ = Intercept on the efficiency axis

$(-)m$ = Slope

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

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

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

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

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:

$$b = F_R \tau\alpha$$

and (6)

$$m = F_R U_L$$

where the terms are as previously defined

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

In deriving the collector array efficiency curves by the linear regression technique, measurement data over the entire performance period yields higher confidence in the results than similar analysis over shorter periods. Over the longer periods the collector array is forced to operate over a wider dynamic range. This eliminates the tendency shown by some types of solar energy systems* to cluster efficiency values over a narrow range of operating points. The clustering effect tends to make the linear regression technique approach constructing a line through a single data point. The use of data from the entire performance period results in a collector array efficiency curve that is more accurate in long-term solar system performance prediction. The long-term curve, the curve derived from the laboratory single panel data, and the MSFC test curve [9] are shown in Figure 3.2.1-2.

The three curves of Figure 3.2.1-2 do not show the significant differences that similar analysis studies done on other collectors have shown. In fact, the crossover point of the three curves falls within the operating point range where most of the collector operation occurred, as can be seen from the histograms of Figure 3.2.1-3.

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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.

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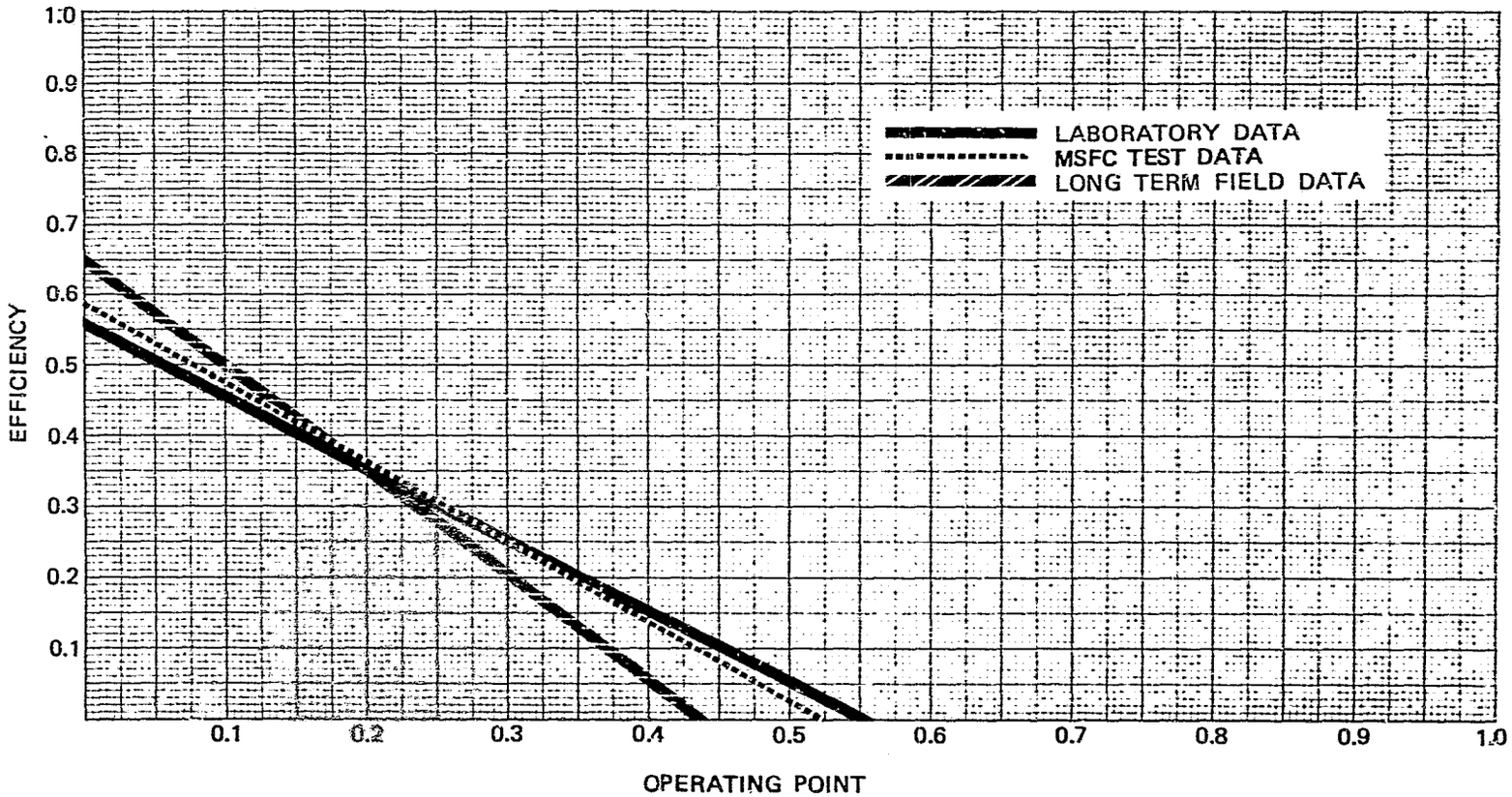
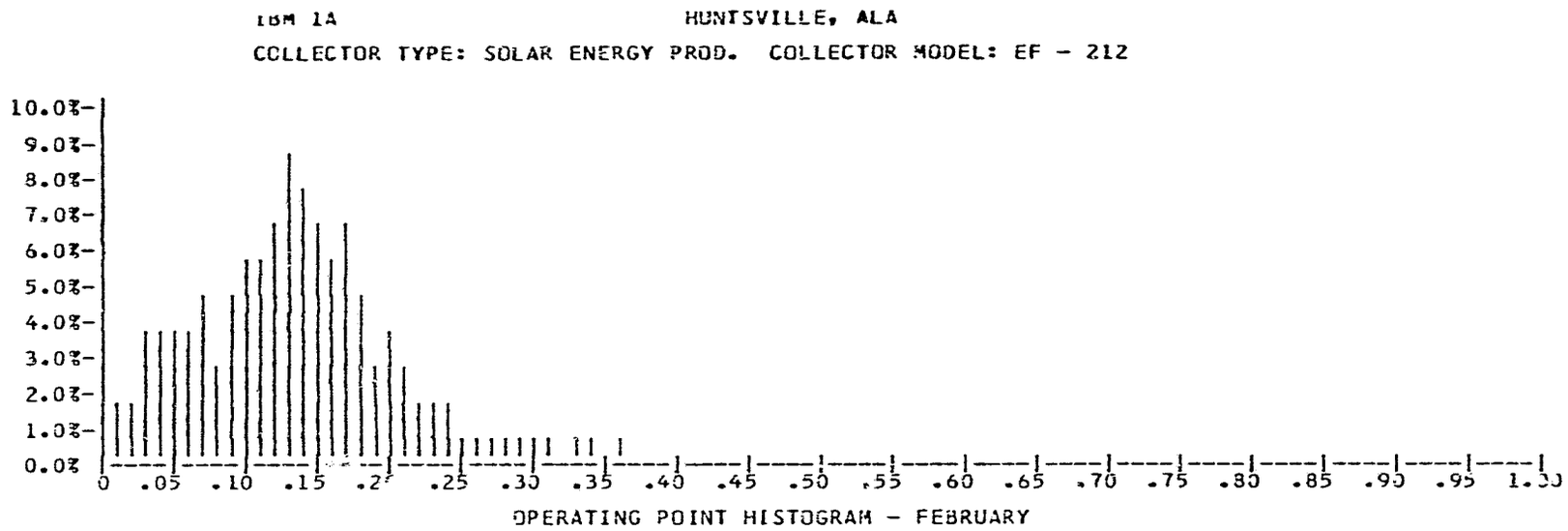



Figure 3.2.1-2 IBM System 1A Collector Efficiency Curves



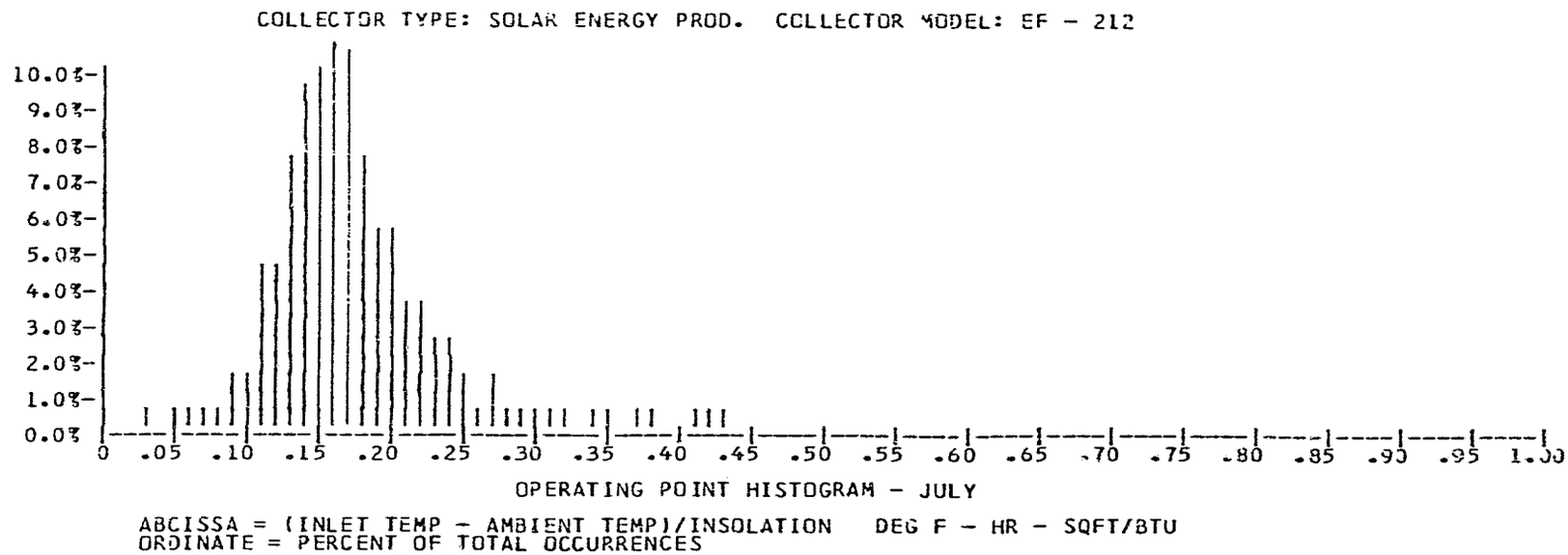




Figure 3.2.1-3 IBM System 1A Operating Point Histogram for Typical Winter and Summer Months

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

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

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

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

   b. The laboratory single panel collector efficiency curve

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

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

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

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 condition 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 IBM System 1A site the average error computed from the difference between the measured solar energy collected and the predicted solar energy collected based on the field derived long-term collector array efficiency curve was 0.6 percent. For the curve derived from the laboratory single panel data, the error was 6.1 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 0.13 and for July at 0.16.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the 12 month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equations (1) and (2). The values of operational collector efficiency range from a maximum of 0.61 in February 1979 to a minimum of 0.23 in September 1979. On the average the operational collector array efficiency exceeded the collector array efficiency which included the effect of the control system by 19 percent.

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

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: IBM System 1A

Huntsville, Alabama

| MONTH/YEAR | COLLECTED SOLAR ENERGY (MILLION BTU) | ERROR | |
|---|---|---|---|
| | | FIELD DERIVED LONG TERM | LAB PANEL |
| Sep 78 | 1.445 | -0.024 | -0.448 |
| Oct 78 | 4.784 | -0.022 | -0.071 |
| Nov 78 | 5.543 | 0.128 | 0.182 |
| Dec 78 | 0.000 | 0.000 | 0.000 |
| Jan 79 | 5.312 | 0.321 | 0.439 |
| Feb 79 | 5.478 | 0.177 | 0.365 |
| Mar 79 | 9.858 | -0.041 | 0.084 |
| Apr 79 | 5.296 | -0.068 | 0.024 |
| May 79 | 2.588 | -0.386 | -0.348 |
| Jun 79 | 2.434 | -0406 | -0.392 |
| Jul 79 | 1.932 | -0.394 | -0.386 |
| Aug 79 | 0.000 | 0.000 | 0.000 |
| Average | 4.467 | -0.006 | 0.061 |

### 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

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

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

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

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

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

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

$$C = (Q_{si} - Q_{so} - \Delta Q)/[(\overline{T}_s - \overline{T}_a) \times t] \frac{Btu}{Hr\text{-}°F} \qquad (8)$$

where

$C$ = Effective storage heat transfer coefficient

$Q_{si}$ = Energy to storage

$Q_{so}$ = Energy from storage

$\Delta Q$ = Change in stored energy

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

$\overline{T}_a$ = Average ambient tempeature in the vicinity of storage

$t$ = Number of hours in the month

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

The six month average storage efficiency was 42.5 percent. Rock storage was used only six months from November 1978 through April 1979.

TABLE 3.2.2-1

STORAGE SUBSYSTEM PERFORMANCE

| Month | Energy To Storage (Million Btu) | Energy From Storage (Million Btu) | Change In Stored Energy (Million Btu) | Storage Efficiency | Storage Average Temperature (°F) | Effective Storage Heat Loss Coefficient (Btu/Hr°F) |
|---|---|---|---|---|---|---|
| Nov 78 | 2.743* | 1.288 | -0.254 | 0.377 | 106 | 41 |
| Dec 78 | 6.874 | 3.967 | 0.032 | 0.582 | 89 | 112 |
| Jan 79 | 4.005 | 2.274 | 0.091 | 0.591 | 75 | 122 |
| Feb 79 | 4.016 | 2.332 | 0.095 | 0.605 | 81 | 97 |
| Mar 79 | 8.630 | 2.376 | 0.561 | 0.340 | 107 | 115 |
| Apr 79 | 4.746* | 0.200 | 0.068 | 0.056 | 106 | 104 |
| Total | 31.014 | 12.437 | 0.593 | -- | -- | -- |
| 6-Month Average | 5.169 | 2.073 | 0.099 | 0.425 | 94 | 98 |

*System in "Summer Mode" part of month.

The storage efficiency values are more closely related to usage than to the design and quality of the storage container. If the energy placed in storage is not used in a short period of time (hours), this energy escapes from storage to the lower temperature surroundings. The rectangular storage enclosure at the IBM System 1A site was located with one wall exposed to outside environment and three walls exposed to inside environment. The bottom of storage was a concrete slab on the ground. Heat loss from storage went to the outside, to the building and to the ground. Additional insulation was added to the bottom of rock storage on December 5, 1978. This addition had very little affect on the losses. The unmeasured energy lost from storage through the three inside walls and through imperfect damper seals helped heat the building.

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

### 3.2.3 Hot Water Subsystem

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

The performance of the IBM System 1A hot water subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in Table 3.2.3-1 is the gross energy supplied to the auxiliary system. The value of auxiliary energy supplied multiplied by the auxiliary system efficiency gives the auxiliary thermal energy actually delivered to the load. The difference between the sum of auxiliary thermal energy plus solar energy and the hot water load is equal to the thermal (standby) losses from the hot water subsystem.

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

For the 12-month period from September 1978 through August 1979, the solar energy system supplied a total of 3.816 million Btu to the hot water load. The total hot water load for this period was 1.606 million Btu, and the weighted average monthly solar fraction was 51 percent.

The monthly average hot water load during the reporting period was 0.134 million Btu. This is based on an average daily consumption of 9 gallons, delivered at an average temperature of 128°F and supplied to the system at an average temperature of 64°F. The temperature of the supply water ranged from a low of 48°F in February to a high of 76°F in August.

Each month an average of 0.318 million Btu of solar energy and 0.211 million Btu of auxiliary thermal electrical energy were supplied to the hot water subsystem. Since the average monthly hot water load was 0.134 million Btu, an average of 0.395 million Btu was lost from the hot water tanks each month. Additional insulation was added to the hot water tank on December 5, 1978. Losses from the tank were reduced by approximately 20 percent.

Table 3.2.3-1

Hot Water Subsystem Performance

| Month | Energy Supplied (Million Btu) | | | | Hot Water Load (Million Btu) | Average Daily Usage (Gal.) | Hot Water Standby Losses (Million Btu) | Weighted** Solar Fraction (Percent) |
|---|---|---|---|---|---|---|---|---|
| | Auxiliary | Auxiliary* Thermal | Solar | Total | | | | |
| Sep 78 | 0.331 | 0.331 | 0.359 | 0.690 | 0.083 | 5 | 0.607 | 40*** |
| Oct 78 | 0.392 | 0.392 | 0.424 | 0.816 | 0.178 | 9 | 0.638 | 38*** |
| Nov 78 | 0.358 | 0.358 | 0.348 | 0.706 | 0.165 | 9 | 0.541 | 35*** |
| Dec 78 | 0.175 | 0.175 | 0.309 | 0.484 | 0.080 | 5 | 0.404 | 55 |
| Jan 79 | 0.304 | 0.304 | 0.309 | 0.613 | 0.196 | 12 | 0.417 | 38 |
| Feb 79 | 0.228 | 0.228 | 0.169 | 0.397 | 0.209 | 12 | 0.188 | 43 |
| Mar 79 | 0.148 | 0.148 | 0.216 | 0.364 | 0.064 | 4 | 0.300 | 46 |
| Apr 79 | 0.140 | 0.140 | 0.251 | 0.391 | 0.092 | 6 | 0.299 | 50 |
| May 79 | 0.124 | 0.124 | 0.285 | 0.409 | 0.067 | 5 | 0.342 | 46 |
| Jun 79 | 0.108 | 0.108 | 0.396 | 0.504 | 0.162 | 13 | 0.342 | 81 |
| Jul 79 | 0.132 | 0.132 | 0.342 | 0.474 | 0.160 | 13 | 0.314 | 61 |
| Aug 79 | 0.092 | 0.092 | 0.408 | 0.500 | 0.150 | 12 | 0.350 | 78 |
| Total | 2.532 | 2.532 | 3.816 | 6.348 | 1.606 | -- | 4.742 | -- |
| Average | 0.211 | 0.211 | 0.318 | 0.529 | 0.134 | 9.75 | 0.395 | 51 |

*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.

***Prior to November 22, hot water heater set at 148°F. After November 22 the hot water heater setting was lowered to 124°F.

Hot water usage at the IBM System 1A site averaged 9 gallons per day (much less than normal single family dwelling usage). The hot water solar fraction varied from 35 percent to 81 percent. The 81 percent solar fraction was for June 1979 when the system was in the summer mode and usage averaged 13 gallons per day. The prior month when usage averaged only 5 gallons per day, solar fraction was 46 percent. Additional hot water usage would have allowed better utilization of hot water preheat (two tank) subsystem. Seventy five percent of the energy put into the hot water subsystem went for tank losses. With more hot water usage (20 to 40 gallons per day) more solar would have been used to meet the load than went to tank losses.

Typically only a fair solar day was required for the preheat tank to be charged. Four hours of collector operation would result in 40° to 60°F temperature rise in the preheat tank during the heating season. During the summer mode this same temperature rise could be obtained in two and one half hours due to bypassing storage and allowing the collector air to run hotter.

### 3.2.4 Space Heating Subsystem

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

The performance of the IBM System 1A space heating subsystem is presented in Table 3.2.4-1. For the 6-month period from November 1978 through April 1979, the solar energy system supplied a total of 17.760 million Btu to the space heating load. The total heating load for this period was 58.496 million Btu, and the weighted average monthly solar fraction was 31 percent.

The measured space heating subsystem performance was lower than expected during the reporting period. January and February were colder and more cloudy than expected. If these two months had been near normal, the weighted average solar fraction would have exceeded 40 percent. The average inside building temperature for the months of January and February were 71°F and 74°F. The design temperature inside the building was 70°F. Often the temperature was maintained at 76°F during the working hours at the building. Maintaining these warm temperatures during the coldest months resulted in larger than expected heating loads.

During the transition months (September, October, April and May) the system did not provide the expected high percentage of the small heating loads. The system was switched back to the summer mode frequently so that cooling could be supplied to the building. The system was then left in the summer mode until a day or so later when heat was needed. At this time the system

TABLE 3.2.4-1

SPACE HEATING SUBSYSTEM PERFORMANCE

| Month | Space Heating Load (Million Btu) | Energy Supplied (Million Btu) | | | Measured Solar Fraction (Percent) |
|---|---|---|---|---|---|
| | | Solar | Auxiliary Thermal | Auxiliary | |
| Nov 78 | 1.926 | 1.510 | 0.415 | 0.278 | 78 |
| Dec 78 | 10.532 | 5.222 | 5.309 | 3.139 | 50 |
| Jan 79 | 23.778 | 4.042 | 19.736 | 10.896 | 17 |
| Feb 79 | 17.326 | 3.655 | 13.671 | 7.851 | 21 |
| Mar 79 | 4.212 | 3.070 | 0.472 | 0.596 | 73 |
| Apr 79 | 0.722 | 0.261 | 0.162 | 0.206 | 36 |
| 6-Month Total | 58.496 | 17.760 | 39.765 | 22.966 | -- |
| 6-Month Average | 9.749 | 2.960 | 6.628 | 3.828 | 31 ** |

*System in "Summer Mode" these months.

**Weighted Solar Fraction: $\sum \frac{\text{Space Heating Load}}{\text{Total Load}} * \text{Measured Solar Fraction}$

was switched to winter mode and auxiliary was used to heat the building since solar had not been allowed to store any energy.

As mentioned in Section 3.2.2 some of the losses from rock storage provided heat to the building. Insulation in the walls (however thick) will eventually allow the heat from storage to escape. Duct work will leak even though installed properly and dampers used in building heating systems leak. Although the site hardware was properly installed and checked, some losses from the ducts and rock bed storage occurred and added unmeasured heat to the building.

## 4. OPERATING ENERGY

Operating energy for the IBM System 1A Solar Energy System is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of air handler blower power and hot water preheat pump power.

Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Table 4.1.

For the September 1978 through August 1979 period covered by this report a total of 7.72 million Btu of operating energy was consumed. During the same time a total of 21.58 million Btu of solar energy was supplied to the total system load.

Therefore, for every one million Btu of solar energy delivered to the load, 0.36 million Btu (or 105 kwh) of electrical operating energy was expended.

TABLE 4-1

OPERATING ENERGY

| Month | ECSS Operating Energy (Million Btu) | Hot Water Operating Energy (Million Btu) | Space Heating Operating Energy (Million Btu) | Total System Operating Energy (Million Btu) |
|---|---|---|---|---|
| Sep 78 | 0.217 | 0.019 | 0.001 | 0.238 |
| Oct 78 | 0.330 | 0.020 | 0.013 | 0.365 |
| Nov 78 | 0.434 | 0.020 | 0.101 | 0.556 |
| Dec 78 | 0.520 | 0.033 | 0.624 | 1.178 |
| Jan 79 | 0.290 | 0.024 | 1.491 | 1.807 |
| Feb 79 | 0.275 | 0.022 | 1.135 | 1.432 |
| Mar 79 | 0.547 | 0.028 | 0.099 | 0.674 |
| Apr 79 | 0.265 | 0.023 | 0.028 | 0.316 |
| May 79 | 0.297 | 0.026 | 0.001 | 0.324 |
| Jun 79 | 0.284 | 0.025 | 0.000 | 0.309 |
| Jul 79 | 0.232 | 0.021 | 0.000 | 0.254 |
| Aug 79 | 0.244 | 0.022 | 0.000 | 0.267 |
| Total | 3.935 | 0.283 | 3.493 | 7.720 |
| Average | 0.328 | 0.024 | 0.291 | 0.643 |

## 5. ENERGY SAVINGS

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy.

Energy savings for September 1978 through August 1979 are presented in Table 5-1. For this time period, the average gross monthly savings were 0.782 million Btu. After the ECSS subsystem operating energy was deducted, the average net monthly electrical savings were 0.454 million Btu, or 133 kwh. For the overall time period covered by this report the total net savings were 5.446 million Btu, or 1596 kwh.

The yearly COP of the heat pump auxiliary heating system was 1.7. Normally a COP of 2.0 would be expected. The thermostat was moved often such as setting back to 70°F for night and advancing to 78°F the next morning. If the thermostat was advanced more than approximately 2°F the backup strip heat came on with the heat pump if solar could not carry the load. Since the COP was low, the use of strip heat was greater than expected.

If the solar energy system had been used only from early November to late March, savings would have been 21 percent more for the year. The system did not save energy or money operating during the warm months only to preheat the hot water. A much larger hot water usage would be required for this system to operate economically for hot water preheating only. During the winter months preheating the hot water does add 5 percent or so to the monthly savings even with the very small hot water usage.

Based on the energy savings and the heating and hot water loads at the site, the solar energy system should be used only during the heating season and turned off during the remainder of the year.

TABLE 5-1

ENERGY SAVINGS

| Month | Electrical Energy Savings (Million Btu) | | ECSS Operating Energy (Million Btu) | Total Electrical Net Savings | |
|---|---|---|---|---|---|
| | Hot Water | Space Heating | | (Million Btu) | (Kwh) |
| Sep 78 | 0.039 | 0.000 | 0.217 | -0.175 | -51.3 |
| Oct 78 | 0.110 | 0.000 | 0.330 | -0.220 | -64.5 |
| Nov 78 | 0.072 | 0.692 | 0.434 | 0.327 | 95.8 |
| Dec 78 | 0.027 | 2.478 | 0.520 | 1.984 | 581.3 |
| Jan 79 | 0.082 | 1.945 | 0.290 | 1.736 | 508.6 |
| Feb 79 | 0.089 | 1.748 | 0.275 | 1.563 | 457.9 |
| Mar 79 | 0.036 | 1.501 | 0.547 | 0.990 | 290.1 |
| Apr 79 | 0.056 | 0.061 | 0.265 | -0.147 | -43.1 |
| May 79 | 0.041 | 0.001 | 0.297 | -0.255 | -74.7 |
| Jun 79 | 0.137 | 0.001 | 0.284 | -0.146 | -42.8 |
| Jul 79 | 0.122 | 0.000 | 0.232 | -0.111 | -32.5 |
| Aug 79 | 0.145 | 0.000 | 0.244 | -0.100 | 29.3 |
| Total | 0.956 | 8.427 | 3.935 | 5.446 | 1595.66 |
| Average | 0.080 | 0.702 | 0.328 | 0.454 | 133.0 |

## 6. MAINTENANCE

This section contains the description of the maintenance performed on the solar system during the 12 month period covered by this report. The damper motor in the air handler was replaced on December 18, 1978 and again on September 13, 1979.* Both of the failures were caused by the lubrication in the gear box drying out in the high temperature environment. The vendor has been unable to correct the problem in the model of the air handler used in this installation. Later versions of the air handler incorporate design changes that may alleviate this problem, but it is anticipated that the System 1A damper motor will continue to need replacement periodically.

* The second replacement was after the reporting period for this system.

## 7. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report provides an operational summary of a solar energy system installed at the Home Builders Association Office Building in Huntsville, Alabama. The system was originally designed for a single family dwelling of approximately 2000 square feet floor space in the Huntsville area. This analysis was conducted by evaluation of measured system performance and by comparison of measured climatic data with long-term average climatic conditions. The performance of major subsystems is also presented.

Measured average daily insolation was low for the year, indicating an abnormally high number of cloudy days. A detail discussion of the insolation data is found in Section 3.1.

The yearly average ambient temperature was 1°F below the long-term average. Measured heating degree days were 3292 compared to 3302 for the long-term average. January and February were colder than average (by 8°F and 4°F), but the other months were near normal or slightly warmer than the long-term average. With the exception of January and February, there was negligible adverse impact on solar system performance due to weather conditions.

The system provided solar energy to the building space heat and hot water loads as expected for the year, providing 30 percent of the space heating and 51 percent of the hot water energy. Due to the very low hot water usage at the site, operating the solar energy system in the summer for hot water only did not prove to be economical. Usage of 25 to 50 gallons per day would have allowed an economical operation. The system did show a good savings by supplying space heating during the five cold months (November through March). Switching from winter to summer or summer to winter operation during the transition months (October and April) resulted in low performance for these months. Several times heat was supplied to the building in the morning and cooling supplied in the afternoon.

The air handler dampers failed to function properly in December 1978. A damper motor assembly was replaced at this time. This was the only hardware failure during the reporting period. The collectors did not show any visible or measurable deterioration during the year. There were no problems with the ducts, rock storage, hot water preheat subsystem or control subsystem. Additional insulation was added to the bottom of storage and to the domestic hot water heater on December 5, 1978. Losses from the domestic hot water heater were reduced by approximately 20 percent. Losses from rock storage were more than expected. The addition of insulation to the bottom of storage had very little (if any) affect on the losses.

In general the disappointing operation of this system is attributed to the manner in which it was used. The system was designed for residential application and used to satisfy the demands of an office environment. The differences were:

- Inside temperature was not maintained at 70°F as expected.
- Hot water usage was much lower than expected.

The conclusion is that the solar energy system must be designed for the type of application in which it is used. Misapplication usually will have an adverse affect on system performance.

## 8. REFERENCES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# APPENDIX A

# DEFINITION OF PERFORMANCE FACTORS

## APPENDIX A
## DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

### COLLECTOR ARRAY PERFORMANCE

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

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

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

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

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

STORAGE PERFORMANCE

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

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

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

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

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

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

## ENERGY COLLECTION AND STORAGE SUBSYSTEM

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

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

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

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

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

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

## HOT WATER SUBSYSTEM

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

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

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

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

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

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

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

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

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

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

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

## SPACE HEATING SUBSYSTEM

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

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

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

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

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

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

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

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

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

## ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as a historical record of weather data for the vicinity of the site.

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

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

- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

# APPENDIX B

# SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS

## APPENDIX B

## SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR IBM SYSTEM 1A

### I. INTRODUCTION

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

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

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

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

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

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

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

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

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

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

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

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

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

where $H_a(T)$ is the enthalpy, in Btu/$lb_m$, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

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

For electrical power, a general example is

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

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

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

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

## EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-2

AVERAGE AMBIENT TEMPERATURE (°F)

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

AVERAGE BUILDING TEMPERATURE (°F)

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

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT$^2$)

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

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

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

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

$$HRF = 0.24 + 0.444 \times HR$$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO OF THE TRANSPORT AIR. THIS FUNCTION IS USED WHENEVER THE HUMIDITY RATIO WILL REMAIN CONSTANT AS THE TRANSPORT AIR FLOWS THROUGH A HEAT EXCHANGING DEVICE

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

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

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

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

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

SOLAR ENERGY TO STORAGE (BTU)

STEI = Σ [M100 x HWD (T151, T101)] x Δτ

SOLAR ENERGY FROM STORAGE TO SPACE HEATING (BTU)

STEO6 = Σ [M400 x HWD (T101, T151)] x Δτ

AVERAGE TEMPERATURE OF STORAGE (°F)

TSTM = (1/60) x Σ [(T200 + T202)/2] x Δτ

TOTAL ENERGY USED BY SPACE HEATING SUBSYSTEM (BTU)

HEAT = Σ [(M400 x (T450 - T400) + M400 x (T402 - T452)) x HRF] x Δτ

TOTAL ENERGY USED BY HOT WATER SUBSYSTEM (BTU)

HWSE = [M300 * HWD (T350, T300)] x Δτ

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

CSEO = HEAT + HWSE

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

CSEO = STEO6

WHEN SPACE HEATING FROM STORAGE

HEATING AUXILIARY ENERGY

HAE = 56.8833 x Σ (EP400 + EP401 + EP403) x Δτ

ECSS OPERATING ENERGY (BTU)

$CSOPE = 0.5 \times 56.8833 \times \Sigma\ EP101 \times \Delta\tau$

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

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

WHEN CHARGING STORAGE

SPACE HEATING SUBSYSTEM SOLAR OPERATING ENERGY (BTU)

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

WHEN SPACE HEATING FROM THE COLLECTOR ARRAY

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

WHEN SPACE HEATING FROM STORAGE

HOT WATER CONSUMED (GALLONS)

$HWCSM = \Sigma\ WD303 \times \Delta\tau$

HOT WATER LOAD (BTU)

$HWL = \Sigma\ [M303 \times HWD(T303, T352)] \times \Delta\tau$

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

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

HOT WATER OPERATING ENERGY

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

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

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

WHEN SYSTEM USING SOLAR ENERGY FOR HEATING

AUXILIARY ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HAT = \Sigma\ [M400 * (T402 - T452) * HRF] \times \Delta\tau$

WHEN SYSTEM USING AUXILIARY ENERGY FOR HEATING

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

WHEN SPACE HEATING FROM AUXILIARY

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

HOPE = HOPE1 + HOPE2

SUPPLY WATER TEMPERATURE (°F)

TSW = T303

HOT WATER TEMPERATURE (°F)

THW = T352

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

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

SEA = CLAREA x SE

COLLECTED SOLAR ENERGY (BTU/FT$^2$)

SEC = SECA/CLAREA

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

CHANGE IN STORED ENERGY (BTU)

STECH = STECH1 - STECH $1_p$

WHERE THE SUBSCRIPT $_p$ REFERS TO A PRIOR REFERENCE VALUE

STORAGE EFFICIENCY

STEFF = (STECH + STEO)/STEI

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

SEL = CSEO

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

AUXILIARY THERMAL ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWAT = HWAE

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = 100 x HWTKSE/(HWTKSE + HWTKAUX)

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

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

HWSVE = HWSE - HWOPE

SPACE HEATING LOAD (BTU)

HL = HAT + HSE

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

HSFR = 100 x HSE/HL

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = (HPFRAC * HL)/ HPCOPH + (1-HPFRAC) * HL - (HAE + HOPE1)

WHERE HPFRAC IS THE FRACTION OF THE TOTAL HEATING LOAD WHICH IS PROVIDED BY THE HEAT PUMP AND HPCOPH IS THE COEFFICIENT OF PERFORMANCE OF THE HEAT PUMP

SYSTEM LOAD (BTU)

SYSL = HL + HWL

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

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

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HOPE + HWOPE

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HWAE + HAE

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HWSVE + HSVE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXE + SECA

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXE + SYSOPE) x 3.33)

# APPENDIX C

# LONG-TERM AVERAGE WEATHER CONDITIONS

## APPENDIX C

## LONG-TERM AVERAGE WEATHER CONDITIONS

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

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

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

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

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SITE: IBM HUNTSVILLE 4. LOCATION: HUNTSVILLE AL

ANALYST: M. STRICKLAND DRIVE NO.: 12.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 34.50 (DEGREES) RUN DATE: 4/11/79

| MONTH | HOBAR | HBAR | KBAR | RBAR | SBAR | HDD | CDD | TBAR |
|---|---|---|---|---|---|---|---|---|
| JAN | 1620. | 638. | 0.39383 | 1.502 | 958. | 747 | 0 | 41. |
| FEB | 2058. | 889. | 0.43177 | 1.327 | 1179. | 605 | 6 | 44. |
| MAR | 2601. | 1209. | 0.46495 | 1.129 | 1365. | 461 | 21 | 51. |
| APR | 3135. | 1604. | 0.51152 | 0.950 | 1523. | 145 | 45 | 62. |
| MAY | 3437. | 1840. | 0.52759 | 0.830 | 1527. | 32 | 174 | 70. |
| JUN | 3621. | 1943. | 0.53662 | 0.780 | 1516. | 0 | 357 | 77. |
| JUL | 3547. | 1855. | 0.52291 | 0.833 | 1469. | 0 | 450 | 80. |
| AUG | 3264. | 1733. | 0.53094 | 0.896 | 1553. | 0 | 434 | 79. |
| SEP | 2769. | 1423. | 0.51033 | 1.060 | 1509. | 11 | 248 | 73. |
| OCT | 2213. | 1158. | 0.52309 | 1.304 | 1510. | 159 | 72 | 62. |
| NOV | 1720. | 773. | 0.45227 | 1.507 | 1172. | 441 | 0 | 50. |
| DEC | 1496. | 533. | 0.35940 | 1.566 | 912. | 701 | 0 | 42. |

LEGEND:

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

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

KBAR ==> RATIO OF HBAR TO HOBAR.

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

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

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

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

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

## REFERENCES


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

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

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

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


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