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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR COLT PUEBLO, PUEBLO, COLORADO

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

U.S. Department of Energy

Solar Energy

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16. ABSTRACT

This report developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy is one of a series of reports describing the operational and thermal performance of a variety of solar systems installed in Operational Test Sites. The 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 Colt Pueblo Solar Energy System was designed by Colt, Incorporated of Southern California, Rancho Mirage, California to provide space heating and hot water preheating for the U. S. Department of Transportation Test Center at Pueblo, Colorado. The system consists of 583 square feet of Colt A-151 series flat plate liquid collectors, a petroleum-base thermal energy transport fluid, an 1,100 gallon water-filled solar energy storage tank, pumps, heat exchangers, controls and associated plumbing. Cold water passes through a liquid-to-liquid heat exchanger internal to the solar energy storage tank to preheat the water supplied to a 30 gallon electric hot water tank. A parallel circulation loop also operates to transfer solar generated heat to the hot water tank. Solar Energy System piping is protected from freezing with heat tapes. There are five modes of system operation. This Solar Energy System became operational in March 1978.

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1. FOREWORD

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

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

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

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

The Seasonal Report document in conjunction with the Final Report for each Operational Test Site in the Development Program culminates the technical activities which began with the site selection and instrumentation system design in April 1976. The Final Report emphasizes the economic analysis of solar systems performance and features the payback performance based on life cycle costs for the same solar system in various geographic regions. Other documents specifically related to this system are References [1] through [5].*

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*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The Colt-Pueblo solar energy system was designed to provide space heating and hot water preheating for the U.S. Department of Transportation Test Center at Pueblo, Colorado. The energy collection and storage subsystem consists of 583 square feet of flat-plate collectors, a petroleum-based thermal energy transport fluid, and an 1,100-gallon water-filled solar energy storage tank. The collector array faces south at an angle of 45 degrees from the horizontal. A heat exchanger in the solar energy storage tank serves to transfer collected energy to the water in the tank and isolates the collector loop fluid from the water.

When there is a space heating demand, solar heated water is pumped from storage to a liquid-to-air heat exchanger within the space heating supply duct. If solar energy is not sufficient to meet the space heating demand, an auxiliary propane gas furnace provides the required additional energy. The building's air-circulation fan and motor-driven dampers distribute the energy to the building.

Solar energy in storage is also used to preheat domestic hot water (DHW). This is done by utilizing a liquid-to-liquid heat exchanger internal to the solar energy storage tank that will permit cold water to pass through the heat exchanger to the DHW system's 30-gallon hot water tank when hot water demand occurs. The same heat exchanger in storage is used to maintain the DHW tank's temperature when solar storage temperatures are high enough to permit circulation of water between the heat exchanger in storage and the DHW tank. The hot water auxiliary is a standard electric resistance, immersion heater in the 30-gallon domestic hot water tank.

The solar energy system piping is protected from freezing with heat tapes. The system, shown schematically in Figure 2-1, has four modes of solar operation and one conventional heating mode. The sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 [6]. The measurement symbol prefixes: W, T, EP, I and F represent respectively: flow rate, temperature, electric power, insolation, and fossil fuel consumption.

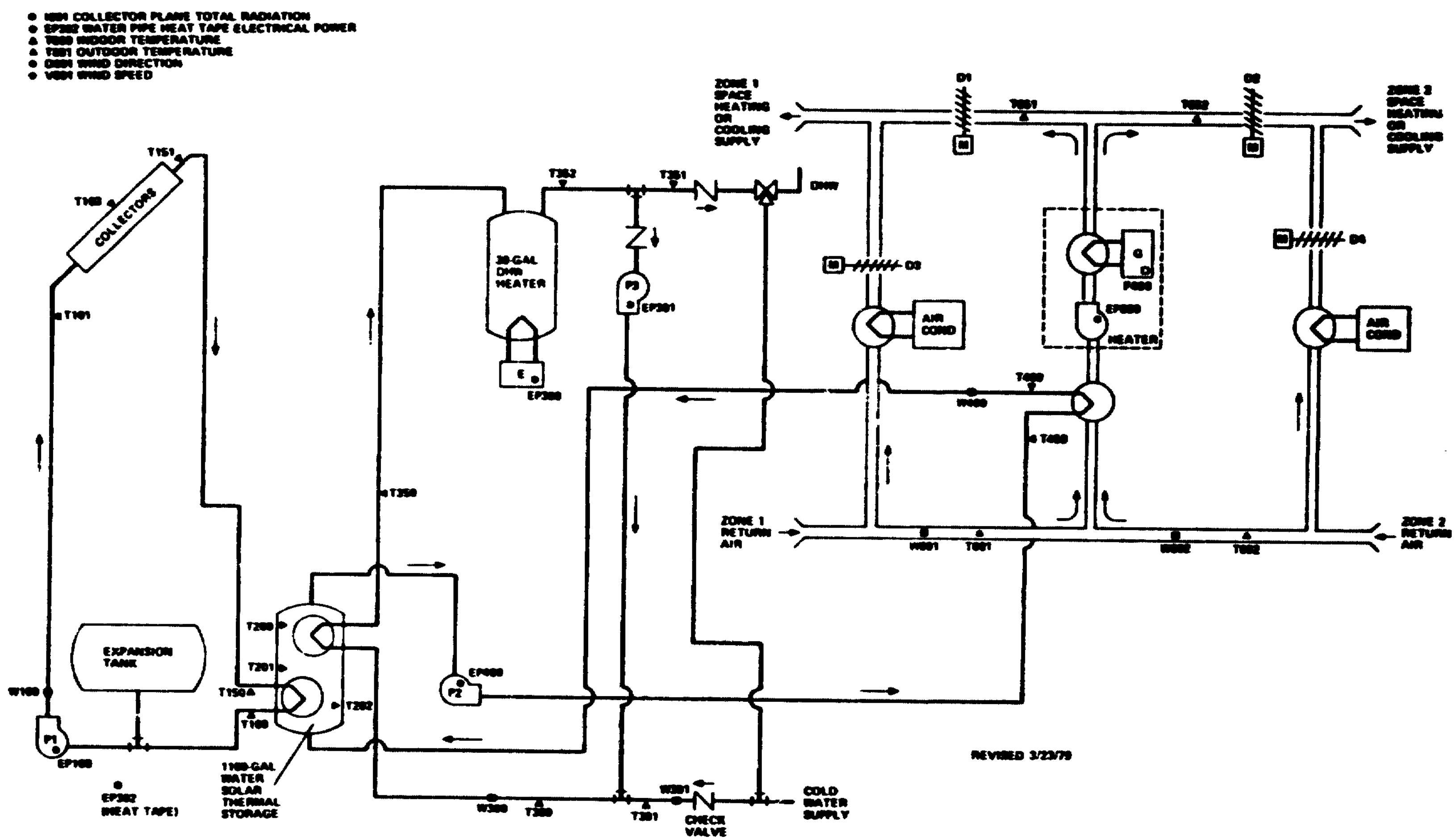


Figure 2-1 Colt-Pueblo Solar Energy System Schematic

Figure 2-2 is a pictorial view of the warehouse, including an expanded view of the collector array.

Mode 1 - Collector-to-Storage: This mode is initiated when a differential controller senses that the indicated collector outlet temperature exceeds the indicated temperature in the top of storage by a predetermined value (nominally 20°F). When the mode is entered, power to pump P1 is applied to circulate collector loop fluid to transfer collected energy to storage. The mode is terminated and pump power turned off when the differential controller recognizes that the indicated collector outlet temperature no longer exceeds the indicated temperature in the top of storage by a predetermined value (nominally 3°F).

Mode 2 - Storage to Space Heating (Solar Only): This mode is initiated when there is a demand for space heating and the indicated temperature in storage is greater than 105°F. When the mode is entered, using pump P2, water is circulated from storage between a liquid-to-air heat exchanger located in the space heating subsystem supply duct and storage. The space heating subsystem supply plenum fan transfers energy to the building. This mode continues until either the indicated thermal storage temperature drops below 105°F or the demand for space heating ceases.

Mode 3 - Storage-to-Space Heating (Solar and Auxiliary): This mode is initiated when there is a demand for space heating, the temperature in storage is lower than 105°F, and the temperature of the water being delivered to the liquid-to-air heat exchanger in the space heating subsystem supply duct is greater than 90°F. Stage two of the space heating thermostat then activates the auxiliary furnace to supplement solar energy to satisfy the demand for heating. Using pump P2, water from storage is circulated between the liquid-to-air heat exchanger located in the supply duct of the space heating subsystem and storage. The space heating subsystem supply plenum fan transfers energy to the building from the heat exchanger and the furnace. This mode continues until thermal storage temperature drops below 90°F or the demand for space heating ceases.

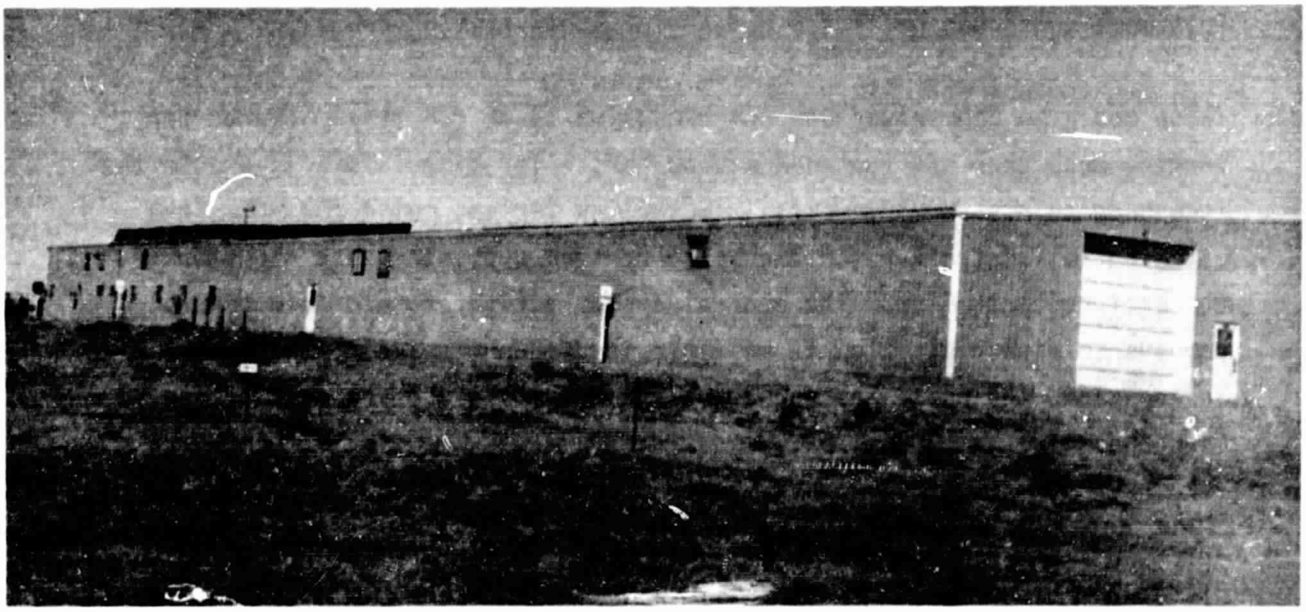


Figure 2-2 Colt Pueblo Warehouse Pictorial and Collector Array Detail

Mode 4 - Hot Water Preheating - This mode is initiated when the indicated solar storage tank temperature is greater than three degrees above the indicated DHW tank temperature. Water is circulated between a heat exchanger internal to storage and the DHW tank to supply solar energy to the DHW tank. This mode is terminated when the storage tank temperature becomes less than three degrees greater than the indicated DHW tank temperature. Hot water preheating also occurs when DHW consumption occurs and the supply water passes through the storage-to-DHW subsystem liquid-to-liquid heat exchanger internal to the solar storage tank.

Electrical power cannot be applied to the DHW tank's auxiliary heater elements during operation of the DHW circulation pump. The auxiliary electric elements only supply additional energy to maintain the DHW temperature at the desired thermostat set point when that temperature cannot be maintained by solar energy storage. This mode is independent of all other modes.

Mode 5 - Conventional Heating: When solar energy for space heating is not available, (i.e., the storage temperature is less than 90°F) stage two of the space heating thermostat activates the auxiliary furnace to supply the required energy to satisfy the demand for heating. The space heating subsystem supply plenum fan transfers energy to the building. This mode continues until the demand for space heating ceases.

These modes in themselves are not exclusive since the system can be performing more than one function at any particular time. This is due to the independence of the differential controller for the collector pump, the differential controller for the space heating subsystem, and the storage temperature controller. The control system activates motorized control dampers to direct air flow to multiple independent space heating zones. In addition, the space heating zones can alternately be heated and cooled independently.

2.1 Typical System Operation

Curves depicting typical system operation on a cool bright day (March 12, 1979) are presented in Figures 2.1-1 (a) through 2.1-1 (e).

Figure 2.1-1 (a) shows the insolation on the collector array and the period when the array was operating (shaded area). On this particular day collector array initiation occurred at 0808 hours and continued to operate until 1612 hours when it was shut down for the day. The insolation reached a peak value of 344 Btu/Hr-Ft^2 at 12:55 P.M.

Figure 2.1-1 (b), 2.1-1 (c), and 2.1-1 (d) show typical collector array temperatures during the day. During the early morning hours the collector array outlet temperature (T151), the collector array inlet temperature (T101) and the collector absorber plate temperature (T103) continued to decay from the temperatures achieved during the previous day's collection. As the sun started to rise at approximately 0630 hours T103 began to rise rapidly and reached 101°F before the system began normal operation at 0808 hours. It should be noted that T103 is not the control sensor that governs system operation. However, the absorber temperature (T103) is in close proximity to the collector control sensor and as such provides an accurate indication of collector plate temperatures in the vicinity of the control sensor. The actual system controls are set up such that a differential temperature of 20°F between the collector and storage is required before collected energy can be delivered to storage. The indicated differential temperature at array initiation was approximately 13.5°F which is less than the expected value. However, no control system switching instabilities occurred.

During the operational period T103 generally tracked the insolation level except when the collector turn-on transient occurred. As would be expected absorber plate temperature reduced during the turn-on transient. The collector outlet temperature (T151) rose to a maximum value of 162°F at 1316 while the collector inlet temperature maximum of 147°F occurred at 1359.

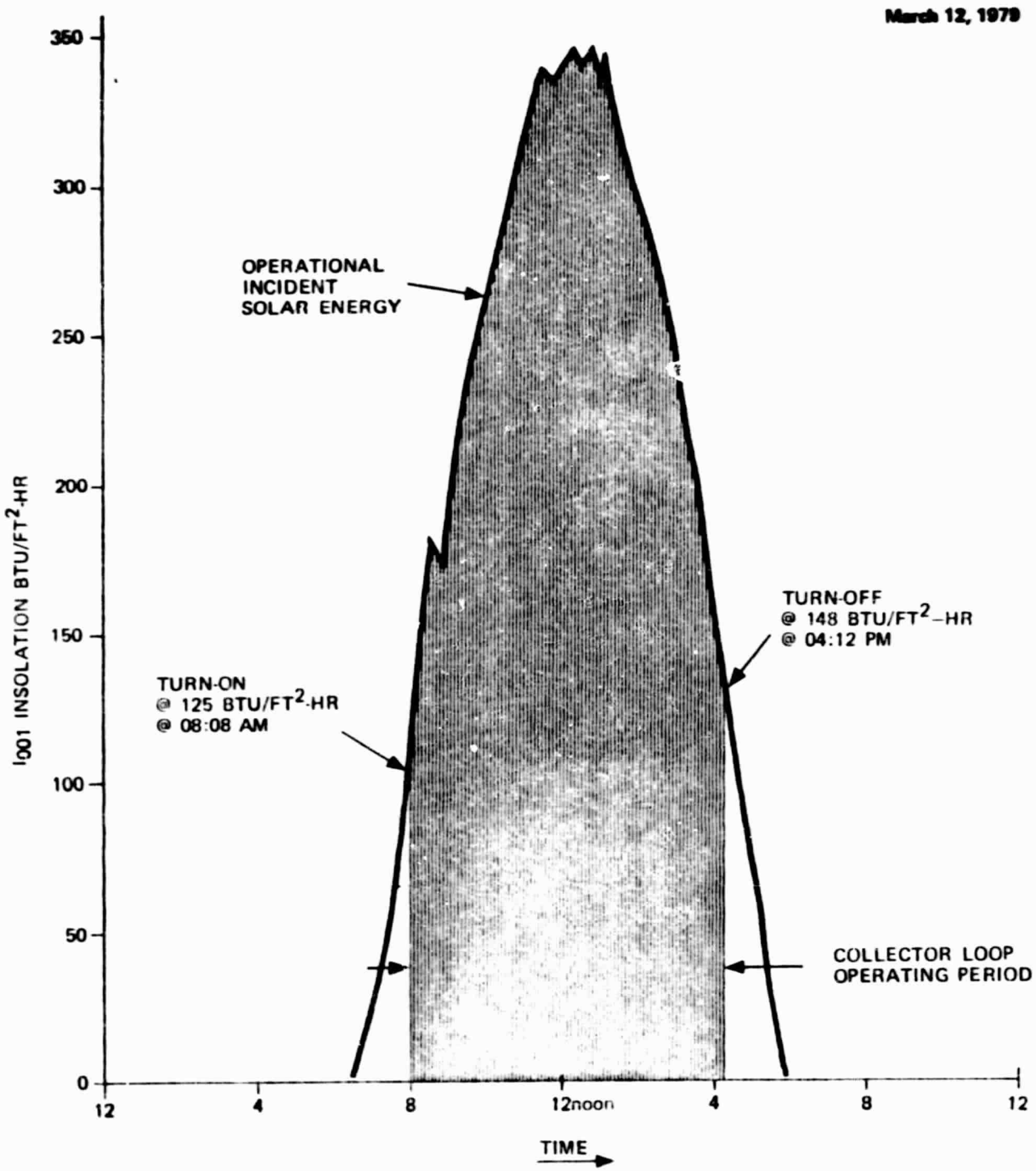


Figure 2.1-1 (a) Solar Insolation vs. Time of Day

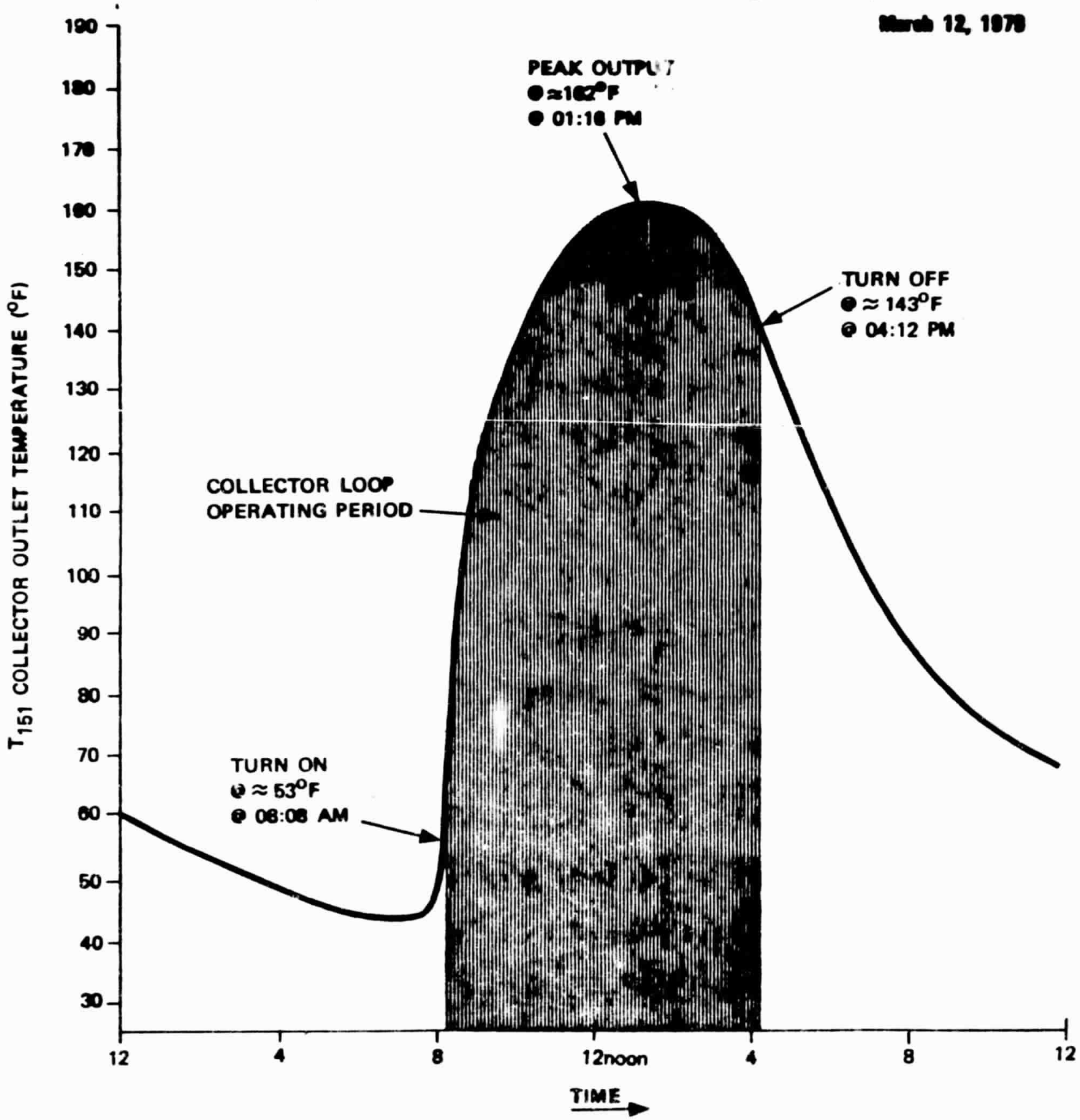


Figure 2.1-1 (b) Collector Outlet Temperature vs. Time of Day

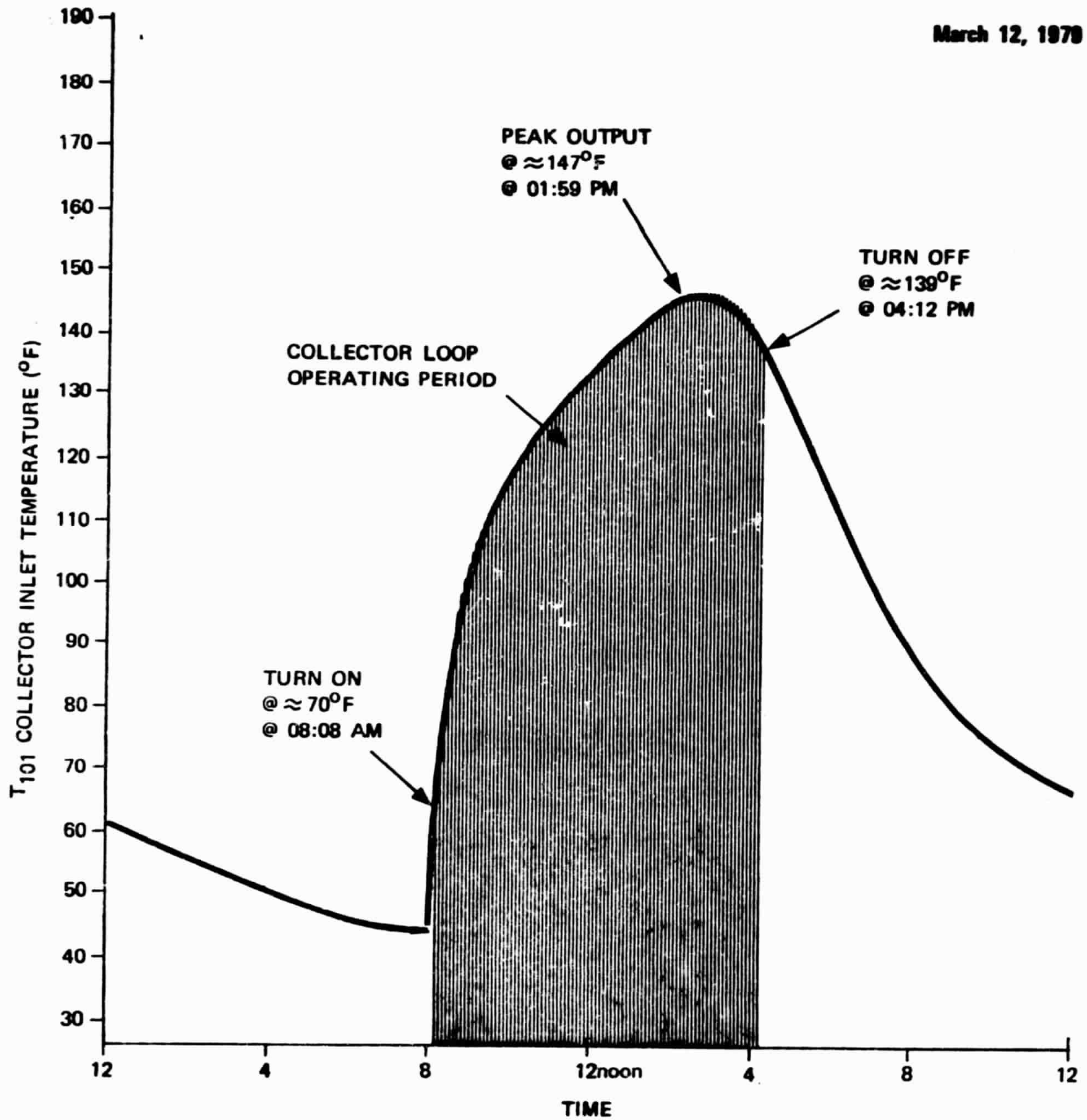


Figure 2.1-1 (c) Collector Inlet Temperature vs. Time of Day

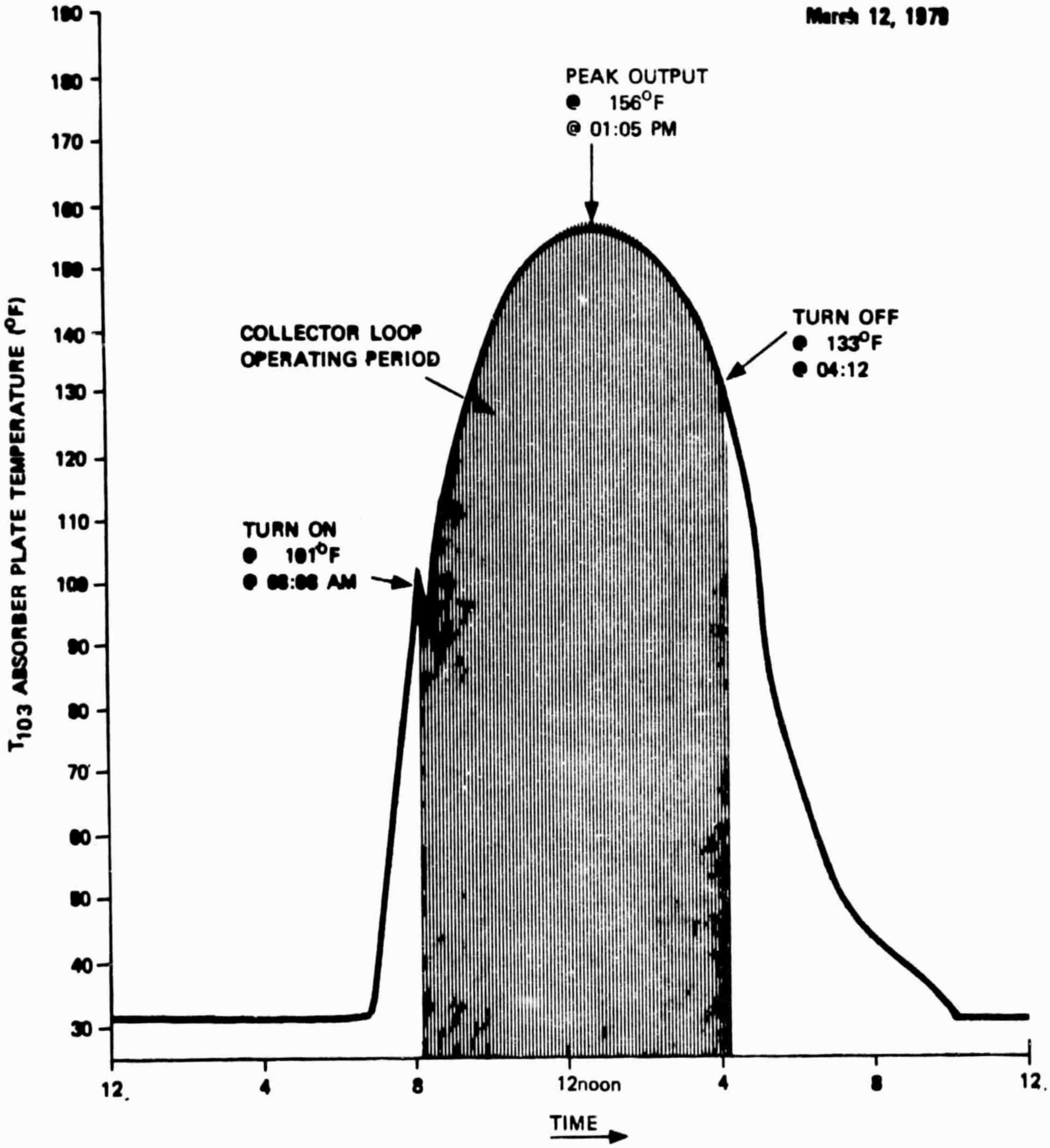


Figure 2.1-1 (d) Absorber Plate Temperature vs. Time of Day

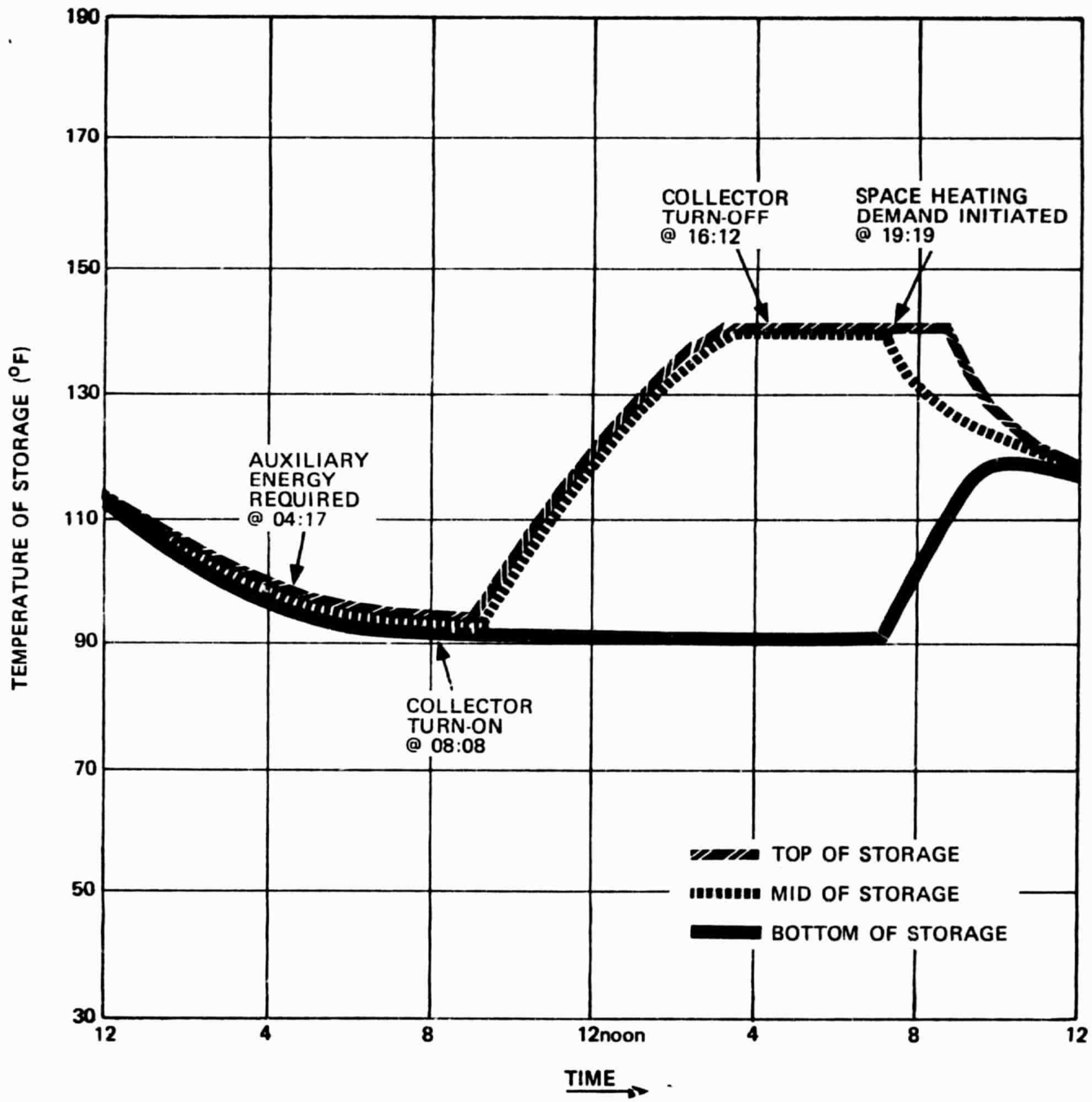


Figure 2.1-1 (e) Storage Tank Temperature Profiles on March 12, 1979

The highest collector inlet and outlet differential temperature achieved was 23.2°F; and, correspondingly the highest collector outlet to storage temperature achieved was 42.8°F both of which occurred at 1103.

Collector array turn-off occurred at 1612 when the collector inlet to outlet temperature reduced below 2°F. The absorber to storage differential was -7°F. Again these temperature differentials are below the design temperature differential of 3°F; however, no control instabilities occurred. These operating temperature constraints are mentioned to make the reader aware that monitoring instrumentation and control sensors do not have direct correlation, but monitoring instrumentation can provide sufficient gross data to determine if each operational mode is functioning within a reasonable range of control temperature sensor limits.

Figure 2.1-1 (e) shows the temperature profile of the 1,100-gallon liquid storage tank. During the early morning hours all space heating demands were satisfied with stored solar energy until 0417 when supplemental auxiliary energy was required. The solar storage subsystem is designed to supply all space heating energy requirements down to a storage temperature of 105°F. Actually, solar energy supplied all space heating needs down to a storage temperature of 95°F. The solar storage tank temperatures continued to decay as energy was removed. Solar and auxiliary energy contributions to space heating continued until 0953 when outside ambient temperatures rose to 61°F and a space heating load no longer existed. After the collector array began operating at 0808, the storage tank began to warm up and continued to do so until the collector array turned off at 1612. The maximum storage temperature achieved was 140°F. Solar energy was used to meet the hot water demands during the day. At 1919, the space heating subsystem began to use stored solar energy for space heating. For the remainder of the day, stored solar energy was able to satisfy most of the space heating demand. The large differential temperature between the top storage temperatures and the bottom temperature is due to the location of the collector loop heat exchanger. Most of the energy transferred to the storage tank is deposited in the top portion of the storage tank. This large temperature stratification continued to exist until a space heating demand occurred. At this time, the storage flow pattern began to mix the fluids in storage and the stratification was eventually eliminated at the end of the day at a combined temperature of 116°F.

2.2 System Operating Sequence

Figure 2.2-1 presents bar charts showing typical system operating sequences for March 12, 1979. This data correlates with the curves presented in Figures 2.1-1 (a) through (e).

There are two interesting observations that can be made from Figure 2.2-1. First is the low DHW usage. The low DHW usage is typical of this solar-energy system. Indeed, the overall DHW solar subsystem savings is less than five percent of the total solar energy system savings for the period of the seasonal report. In the early morning hours, the heat tapes protecting the DHW and space heating energy transport piping were initiated as outdoor temperatures dropped below freezing. In addition to the freeze protection capability, the heat tapes also provide auxiliary thermal energy to the fluid in the transport piping. This auxiliary thermal energy was sufficient to replenish losses from the DHW tank and piping. (The DHW tank is located above the solar storage tank and thermosyphoning can occur.) The heat tape thermal energy transfer continued to occur until 9:15 when outside ambient temperatures rose above 55°F. Later in the morning solar energy transfer from the storage tank was initiated to replenish losses from the DHW tank and piping.

The second observation relates to the use of space heating auxiliary energy. Stored solar energy was sufficient to meet the entire space heating demand until 0417 when the storage tank temperature decayed below 95°F. At this time, the auxiliary propane gas furnace was turned on to supplement solar energy. The auxiliary subsystem is enabled when storage temperatures are below 105°F. At the time of solar collection initiation, storage tank temperatures were still above the threshold temperature, 90°F, necessary for solar energy space heating utilization. Solar and auxiliary energy met the load demands until 9:30. After this time, all demands were met by solar energy from the solar storage tank. This operation is typical of this solar energy system. The solar system is capable of meeting the space heating demand for about seven hours after collector turn-off on good solar days down to temperatures near zero.

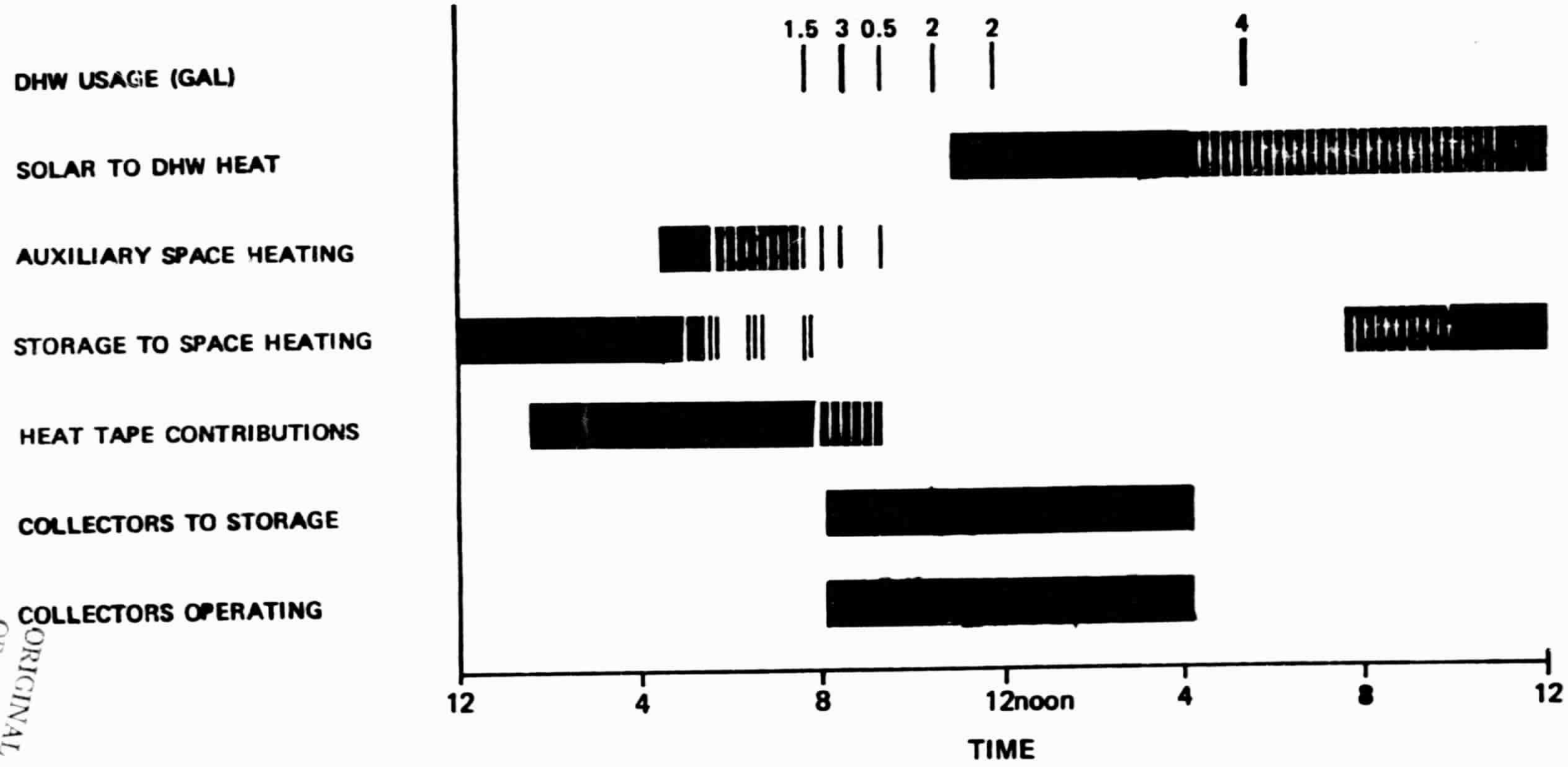


Figure 2.2-1 Typical System Operating Sequence

3. PERFORMANCE ASSESSMENT

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

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

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

The Colt Pueblo Solar Energy System was initially brought on line in early March 1978. At that time all known system problems were addressed and corrected where possible. After the system was started up, a period of data monitoring was initiated to verify that the solar system and monitoring instrumentation were functioning properly.

During the system check-out phase, several solar system deficiencies were found to be present. The solar energy system services the office area which is located in a large unheated warehouse. The thermal energy transport piping, domestic hot water tank (DHW), thermal solar storage tank and air handling ducts are located in the warehouse around, and near the heated office space. Initial observation revealed that the storage tank, connecting pipes and air handling ducts were uninsulated. The solar system remained in this condition until late November, 1978, when the storage tanks, transport piping and air handling ducts were insulated. In addition, the thermal energy transfer piping was wrapped with heat tape to prevent freezing.

In December 1978, the solar thermal storage tank fluid froze and broke the sight glass used to measure the level of water in the storage tank. In addition, a space heating subsystem malfunction caused freezing of water in the DHW piping. As a result of these conditions, the solar storage tank insulation became wet and ineffective. The entire solar system was repaired in early February 1979 by replacing fuzes in the main control circuitry, replacing the insulation on the solar storage tank, and repairing the breaks in the DHW piping.

DHW subsystem operation was improved in March 1979 by installing a new DHW controller. The solar contribution to this subsystem has improved substantially since that event.

In August, the solar storage tank again leaked and had to be repaired.

In January, 1980, a space heating system malfunction again caused the solar energy transport water to freeze. The failure is attributed to a failure of the auxiliary subsystem igniter which apparently will not function in very low temperatures that exist in the warehouse in winter months. The solar water-to-air heat exchanger piping froze and burst. Also, the DHW city water inlet piping froze and destroyed the cold water totalizer used to measure water consumption. These conditions existed until April 11, 1980, when solar space heating was reinitiated.

Because of the solar system deficiencies throughout the monitoring period March 1978 to April 1980, only the period February 1979 through January 1980 is considered representative of proper solar energy system performance. This seasonal report is based on the solar system performance during this period.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the Colt-Pueblo Solar Energy System located in Pueblo, Colorado. 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" [6]. The performance of the major subsystems is also evaluated in subsequent sections of this report.

The measurement data were collected for the period March 1978 through April 1980. However, the Seasonal Report is based on data collected between February 1979 and January 1980. This period represents the best indication of solar system performance. Before and after this evaluation period, the solar system was either inactive or not configured as designed. System performance data were provided through an IBM developed Central Data Processing System (CDPS) [7] consisting of a remote Site Data Acquisition System (SDAS), telephone data transmission lines and couplers, an IBM System 7 computer for data management, and an IBM System 370/145 computer for data processing. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. These data are processed daily and summarized into monthly performance formats which form a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data given in this report.

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

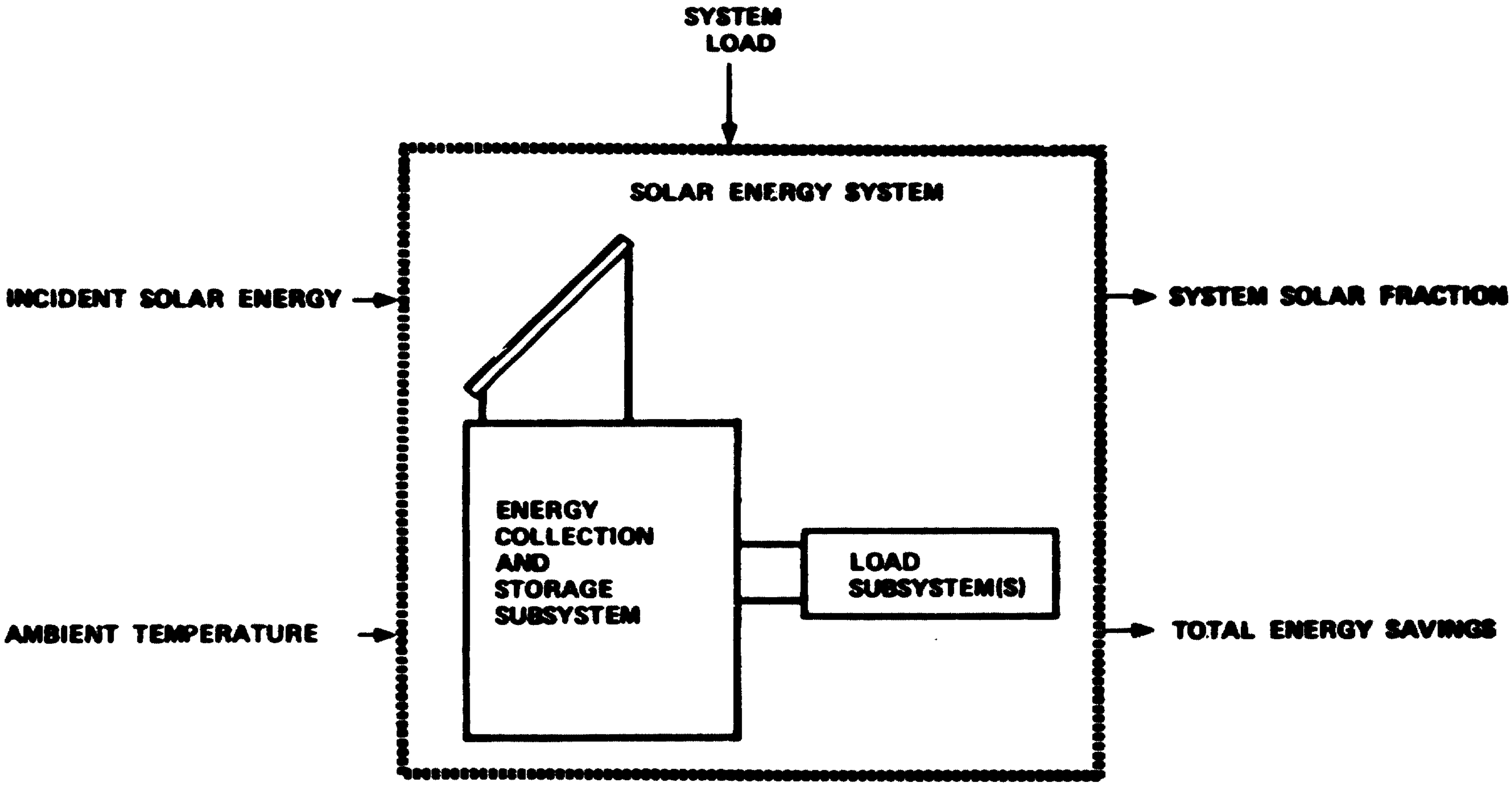


Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

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

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

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

Outputs

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

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

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

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY

COLT PUEBLO

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 Fossil Equivalent At Source** (Million Btu)	Total Energy Savings Fossil Equivalent at Source** Million Btu Without Heat Tape
	Measured	Long-Term Average	Measured	Long-Term Average		Measured	Expected		
Feb 79	1,829	1,811	32	35	29.58	24	34	5.56	10.06
Mar 79	1,730	1,942	42	40	25.99	33	41	13.01	14.68
Apr 79	1,864	1,954	51	52	14.56	45	53	14.36	14.96
May 79	1,332	1,848	56	61	9.23	56	55	14.63	14.63
Jun 79	1,618	1,931	68	71	3.85	67	68	6.80	6.80
Jul 79	1,724	1,896	75	76	1.03	72	71	1.57	1.57
Aug 79	1,784	1,960	73	75	2.66	57	92	4.55	4.55
Sep 79	2,201	2,036	65	66	3.33	39	57	1.67	1.67
Oct 79	1,673	1,983	54	55	6.31	34	68	2.69	3.36
Nov 79	1,702	1,706	33	41	20.70	36	41	4.60	10.07
Dec 79	1,382	1,547	32	33	24.47	24	26	1.63	6.96
Jan 80	1,394	1,694	27	30	30.31	16	23	1.06	4.47
Total	--	--	--	--	172.02	--	--	70.31	93.78
Average	1,681	1,859	51	53	14.34	31*	39	5.86	7.81

*Measured solar fraction is weighted by the system load.

**Total Energy Savings (at source) accounts for the efficiency of delivery of power from the point of generation to the point of use, which is approximately 30 percent.

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

At the Colt-Pueblo site for the 12 month report period, the long-term average daily incident solar energy in the plane of the collector is estimated to be 1,859 Btu/Ft^2. The average daily measured value was 1,681 Btu/Ft^2 which is about ten percent below the long-term value. On a monthly basis, May of 1979 was the worst month with an average daily measured value of incident solar energy 28 percent below the long-term average daily value. September 1979 was the best month with an average daily measured value eight percent above the long-term average daily value. On a long-term basis it is obvious that the good and bad months almost average out so that the long-term average performance should not be adversely influenced by small differences between measured and long-term average incident solar energy.

The outdoor ambient temperature influences the operation of the solar energy system in two important ways. First the operating point of the collectors and consequently the collector efficiency or energy gain is determined by the difference in the outdoor ambient temperature and the collector inlet temperature. This will be discussed in greater detail in Section 3.2.1. Secondly the load is influenced by the outdoor ambient temperature. The measured average daily ambient temperature for the period from February 1979 through January 1980 was 51°F at the Colt-Pueblo site. This compares favorably with the long-term value of 53°F. Thus, the actual heating load during the reporting period should be close to the long-term averages.

It is interesting to note the strong influence that the local weather conditions had on the measured solar fraction. For example, the measured average outdoor ambient temperature in December 1979 was one degree below the long-term average, and in November 1979 it was eight degrees below the long-term average. In December the measured insolation was 11 percent below the long-term average and the measured solar fraction was 24 percent. However, in November the measured insolation was near the long-term average and the measured solar fraction was 36 percent. In March 1979 the measured insolation was eleven percent below the long-term average, but the measured average outdoor ambient temperature of 42°F was two degrees above the long-term average and the measured solar fraction was 33 percent. This is exactly what would be expected because, even though the insolation was low, the measured average outdoor ambient temperature for March was 12°F above that noted for the January-February time period. These observations serve to reinforce the earlier statement concerning the impact of prevailing weather conditions on the performance of a solar energy system.

The system load has an important affect on the system solar fraction and the total energy savings. If the load is small and sufficient energy is available from the collectors, the system solar fraction can be expected to be large. However, the total energy savings will be less than under more nominal load conditions. This is illustrated by comparing the performance of the system during the summer (June, July and August) and winter (December, January and February) months. During the summer the space heating load was negligible and the system was used primarily to support the hot water load. On the other hand, the space heating loads during the winter months were very near the long-term expected values. As a result the system solar fraction was higher than expected in the summer months and near that expected in the winter months.

The system savings were greatly affected by two factors: the heat tape energy requirements in the winter and the low hot water consumption during all months. The heat tape energy requirements (Table 4-1) for the period were 7.13 million Btu and the equivalent cost at the source of energy generation would have been 23.77 million Btu. Thus, a severe penalty is incurred (25 percent of the total possible energy savings) because of the requirement to protect the solar system piping inside the warehouse. Secondly, the low hot water demand resulted in high solar fractions but also high subsystem losses.

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 [11]). The model used in the analysis is based on manufacturers' data and other known system parameters. The basis for the model is a set of empirical correlations developed for liquid and air solar energy systems that are presented in graphical and equation form and referred to as the f-Charts, where 'f' is a designator for the system solar fraction. The output of the f-Chart procedure is the expected system solar fraction. The measured value of system solar fraction was computed from measurements, obtained through the instrumentation system, of the energy transfers that took place within the solar energy system. These represent the actual performance of the system installed at the site.

The measured value of system solar fraction can generally be compared with the expected value so long as the assumptions which are implicit in the f-Chart procedure reasonably apply to the system being analyzed. As shown in Table 3.1-1, the measured system solar fraction of 31 percent was lower than the expected value of 39 percent generated by the modified f-Chart program. The overall performance estimate derived by the collector contractor [COLT, INC.] predicted a solar fraction of 34 percent [1]. Although this variation is substantial, it must be realized that the f-Chart prediction model is not ideally suited to the type of system design used at Colt-Pueblo. For example, the f-Chart model assumes a perfectly insulated tank in the hot water subsystem. This is close to the situation that exists at this site in summer and is the reason that the expected solar fraction (negligible heating load) is relatively close to the actual performance during those months. However, even though the prediction model must use some assumptions that do not fit the solar energy system perfectly, the overall value of this analysis tool should not be underestimated. During the winter months significant variations can generally be attributed to the various uncontrolled energy losses that exist in the system. The affect of the solar system losses in a building such as Colt-Pueblo would require a more sophisticated analytical model than f-Chart.

The total energy savings is the most important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with less expensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment for the system. In terms of the technical analysis presented in this report the net total energy savings should be a significant positive figure. The total computed energy savings for the Colt-Pueblo Solar Energy System was 70.31 million Btu, or 765 gallons of propane, which was a significant amount of energy. This is further illustrated by the 31 percent solar fraction of the measured load achieved by the system. However, this savings is based only on measured inputs of solar energy to the load subsystems. At the Colt-Pueblo site there were a significant amount of uncontrolled (and hence unmeasured) inputs of solar energy into the building. These uncontrolled inputs of solar energy came primarily from transport losses and tended to reduce the overall heating load, which in turn tended to increase real savings. This situation is addressed in more detail in the appropriate sections that follow.

3.2 Subsystem Performance

The Colt-Pueblo Solar Energy Installation may be divided into four subsystems:

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

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

3.2.1 Collector Array Subsystem

The Colt Pueblo collector array consists of twenty Colt A-151 series flat-plate liquid collectors all connected in parallel. These collectors are aluminum roll bond type with a single selective glazing. The viscosity of the petroleum-based thermal energy transport fluid and variable collector inlet temperatures result in individual collector flow which varies from 13.1 gallons per minute in winter to 21.2 gallons per minute in summer. The collector array arrangement is shown pictorially in Figure 3.2.1-1 (a). Details of the collector array liquid flow paths are shown in Figure 3.2.1-1 (b). The collector subsystem analysis and data are given in the following paragraphs.

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

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

where η_c = Collector array efficiency

Q_s = Collected solar energy

Q_i = Incident solar energy

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

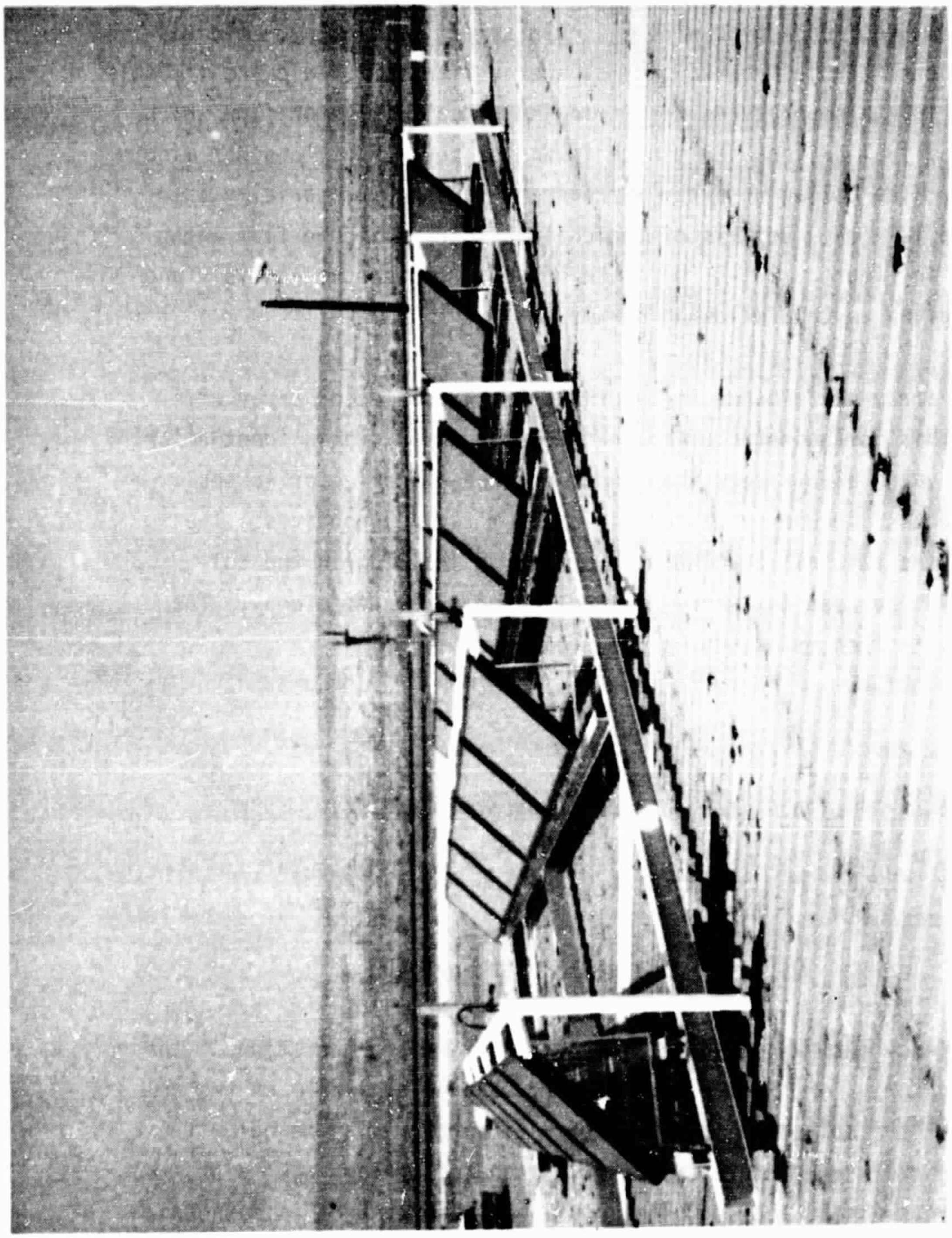
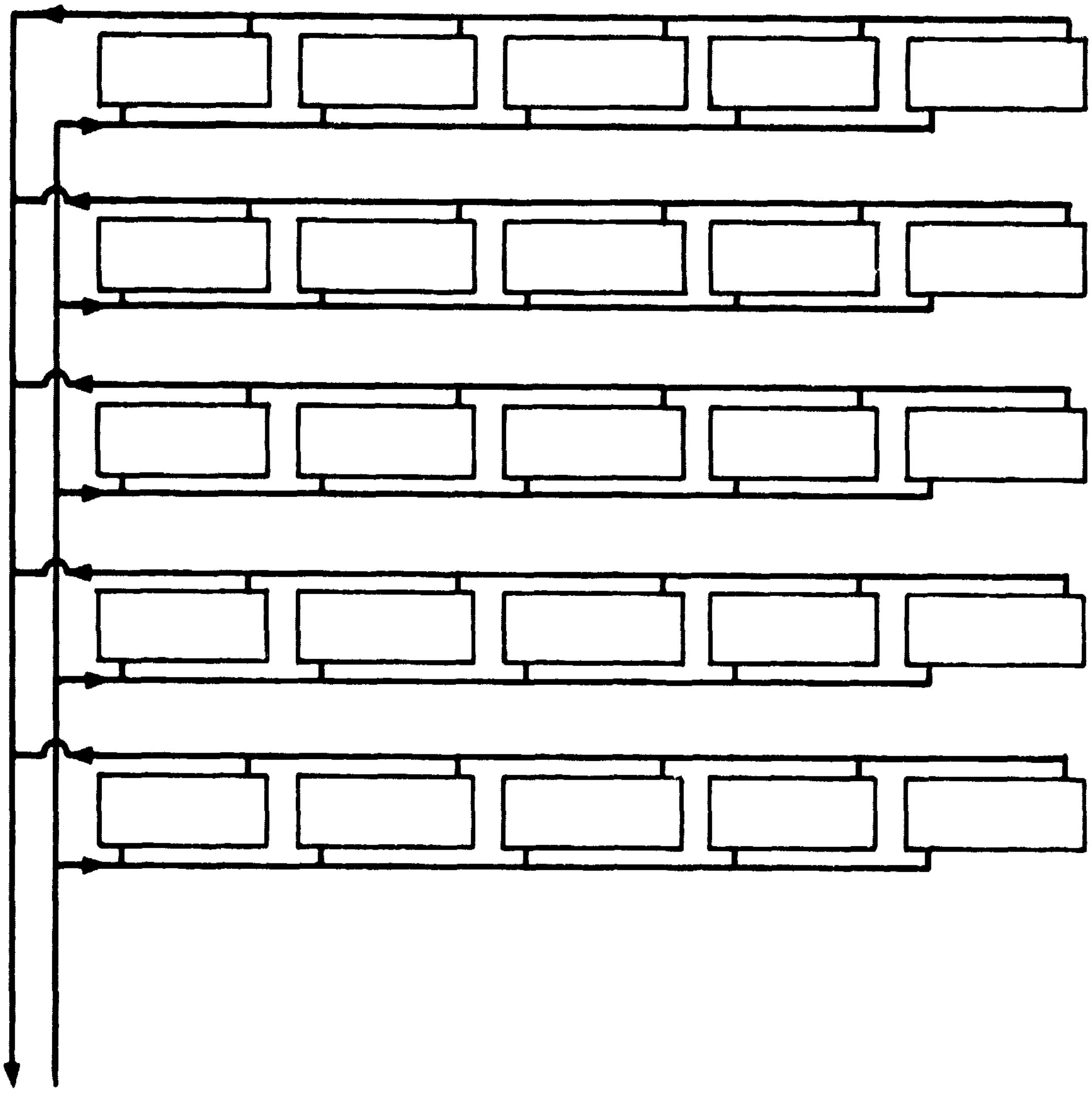


Figure 3.2.1-1 (a) Collector Arrangement



(b) Collector Array Arrangement

COLLECTOR ARRAY		SITE LOCATION	
TILT	– 45°	LATITUDE	– 38.28°N
AZIMUTH	– SOUTH	LONGITUDE	– 104.52°W

Figure 3.2.1-1 (b) Collector Details

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

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

where η_{co} = Operational collector array efficiency

Q_s = Collected solar energy

Q_{oi} = Operational incident solar energy

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

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

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

In the ASHRAE Standard 93-77 [8] 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

TABLE 3.2.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Array Efficiency
Feb 79	29.88	7.74	0.26	25.00	0.31
Mar 79	31.29	8.97	0.29	26.84	0.33
Apr 79	31.56	8.97	0.28	27.01	0.33
May 79	24.08	6.84	0.28	20.08	0.34
Jun 79	28.31	7.01	0.25	22.68	0.31
Jul 79	31.18	3.80	0.12	18.05	0.21
Aug 79	32.26	2.69	0.08	7.89	0.34
Sep 79	38.52	4.92	0.13	16.54	0.30
Oct 79	30.25	3.57	0.12	11.22	0.32
Nov 79	29.79	7.75	0.26	25.79	0.30
Dec 79	25.00	6.51	0.26	21.33	0.31
Jan 80	25.21	5.71	0.23	20.20	0.28
Total	357.33	74.48	--	242.63	--
Average	29.78	6.21	0.21	20.22	0.31

evaluating collectors. The collector evaluation performed for this report using the field data indicates that there was a significant difference between the laboratory single panel collector data and the collector data determined from long-term field measurements. This may or may not always be the case, and there are two primary reasons for differences when they exist:

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

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

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

The long-term data base for Colt-Pueblo includes the months from March 1978 through March 1980. Although the solar energy system was in operation for most of the period, the solar system operated as designed only between February 1979 and January 1980. For consistency, the collector evaluation period was selected to be the same time interval.

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

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

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

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

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

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

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

T_i = Collector inlet temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

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

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

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

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

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

b = Intercept on the efficiency axis

$(-)m$ = Slope

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

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

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

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

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

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

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

where the terms are as previously defined

The discussion of the collector array efficiency curves in subsequent paragraphs is based upon the relationships expressed in Equation (6). However, the single panel curve is not representative of the collector array performance expected of this system. The collector/storage loop contains a heat exchanger in the storage tank. The heat exchanger modifies the collector performance [4, 5]. A heat exchanger modifier (penalty factor) F_R'/F_R (fraction of $F_R U_L$) was determined by MSFC from laboratory test results and/or from collector contractor information. F_R'/F_R is a function of the heat exchanger effectiveness, collector/storage loop capacitance rates and collector array area. Proper sizing of these parameters should result in a F_R'/F_R value greater than 0.90, or a maximum 10 percent energy penalty over the no heat exchanger systems. The $F_R'F_R$ penalty factor for Colt-Pueblo was determined to be 0.803. The $F_R(\tau\alpha)$ and $F_R U_L$ terms are modified appropriately to account for this circumstance.

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

* 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.

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 modified laboratory panel curve are shown in Figure 3.2.1-2. The long-term first order curve shown in Figure 3.2.1-2 has a slightly less negative slope than the curve derived from single panel laboratory test data. This is attributable to lower losses resulting from array effects. The laboratory predicted instantaneous efficiency is not in close agreement with the curve derived from actual field operation. This indicates that the laboratory derived curve might not be useful for design purposes in an array configuration of this type. However, the modified laboratory performance curve, which accounts for the heat exchanger in the collector loop, is in good agreement with the actual measured performance of the collector array. Therefore, the modified collector performance curve would be useful for design purposes when a heat exchanger is employed.

For information purposes the data associated with Figure 3.2.1-2 is as follows:

Single panel laboratory data

$F_R(\tau\alpha) = 0.757$ $\qquad$ $F_R U_L = -1.177$

Modified performance estimate

$F_R(\tau\alpha) = .608$ $\qquad$ $F_R U_L = -0.945$

Long-term field data

$F_R(\tau\alpha) = 0.564$ $\qquad$ $F_R U_L = -0.953$

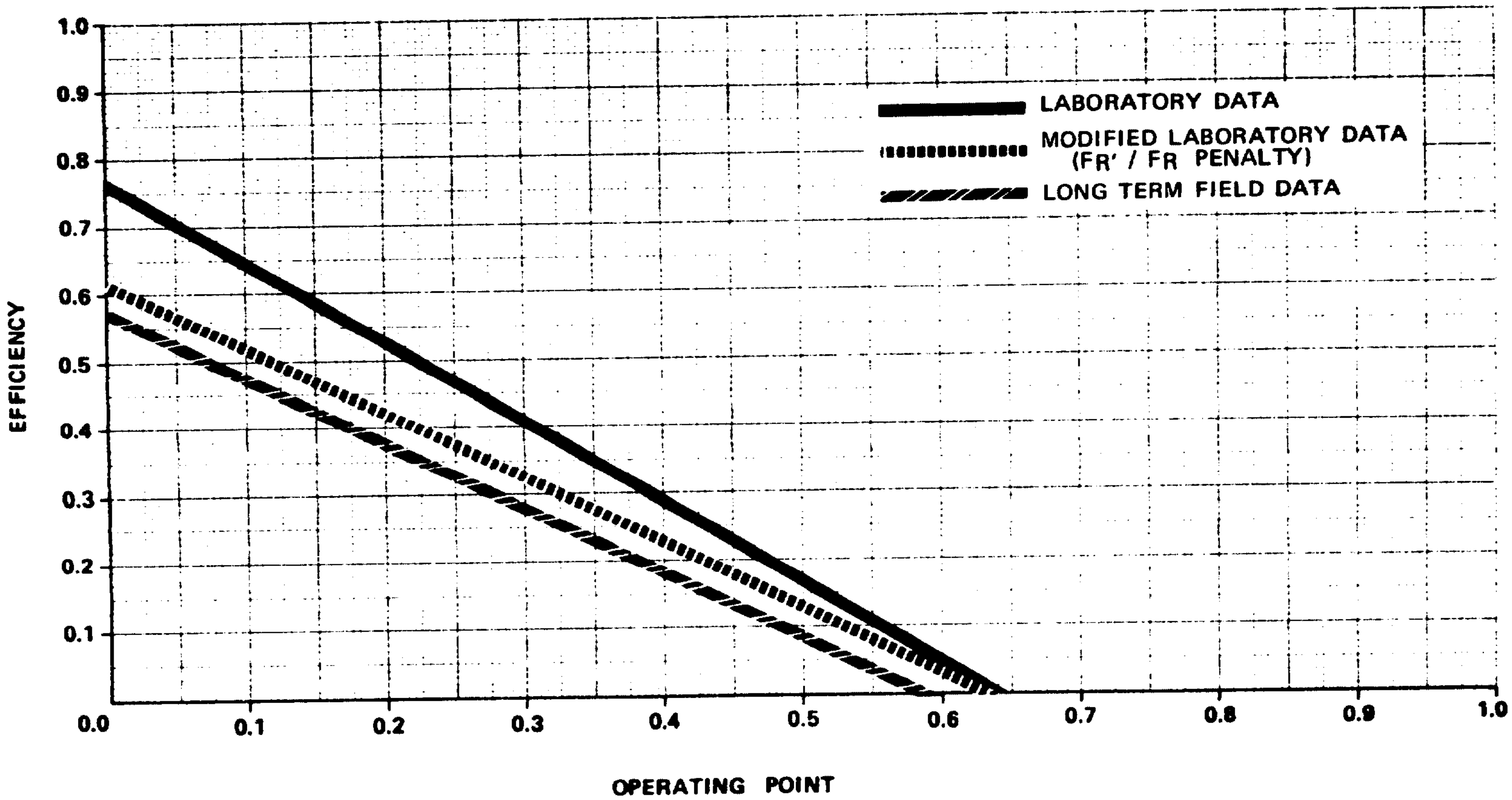


Figure 3.2.1-2 Colt Pueblo Collector Efficiency Curves

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

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

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

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

   b. The laboratory single panel collector efficiency curve

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

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

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

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

TABLE 3.2.1-2

ENERGY GAIN COMPARISON
(ANNUAL)

SITE: COLT PUEBLO PUEBLO, COLORADO

Month	Collected Solar Energy (Million Btu)	Error	
		Field Derived Long-Term	Laboratory Single Panel
Feb 79	7.73	-0.037	-0.202
Mar 79	8.63	-0.023	-0.161
Apr 79	8.58	-0.018	-0.164
May 79	6.81	0.022	-0.127
Jun 79	6.91	-0.127	-0.264
Jul 79	3.26	-0.106	-0.265
Aug 79	3.70	0.021	-0.124
Sep 79	3.23	-0.041	-0.176
Oct 79	3.36	-0.065	-0.201
Nov 79	7.62	-0.049	-0.184
Dec 79	4.43	-0.025	-0.162
Jan 80	5.26	-0.049	-0.184
Average	5.79	-0.040	-0.184

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

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

The data from Table 3.2.1-2 illustrates that for the Colt-Pueblo site the average error computed from the difference between the measured solar energy collected and the predicted solar energy collected based on the field derived long-term collector array efficiency curve was -4 percent. For the curve derived from the laboratory single panel data, the error was -18.4 percent. Thus the long-term collector array efficiency curve gives significantly better results than the laboratory single panel curve. The long-term collector array efficiency curve is in close agreement with the modified laboratory curve. In fact, the slopes are nearly identical and the intercept points are within 8 percent of each other.

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

Another characteristic of the operating point histogram is the shifting of the distribution along the operating point axis. This can be explained in terms of the characteristics of the system and the climatic factors of the site, i.e., incident solar energy and ambient temperature. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (February) and a typical summer month (July) operation. The approximate average operating point for February is at 0.28 and for July at 0.37. From Equation (3), when the temperature difference becomes larger, between T_i and T_a, as a result of switching from winter space heating to summer hot water preheating, the operating point shifts to the right. The operating point during winter months is essentially the same as the February operating point.

Also shown in Figure 3.2.1-3 on the February operating point histogram is the monthly collector array efficiency of 0.31 for February (Table 3.2.1-1) and the February field derived collector array efficiency curve. The intersection of the average operating point for February and the February performance curve implied a monthly efficiency of 0.32. The close agreement between the field derived collector array efficiency and the actual February monthly collector performance indicates that the field derived performance data could be used for design purposes.

Additional information concerning collector array analysis in general may be found in Reference [10]. The material in the reference describes the detailed collector array analysis procedure and presents the results of analyses performed on numerous collector array installations across the United States.

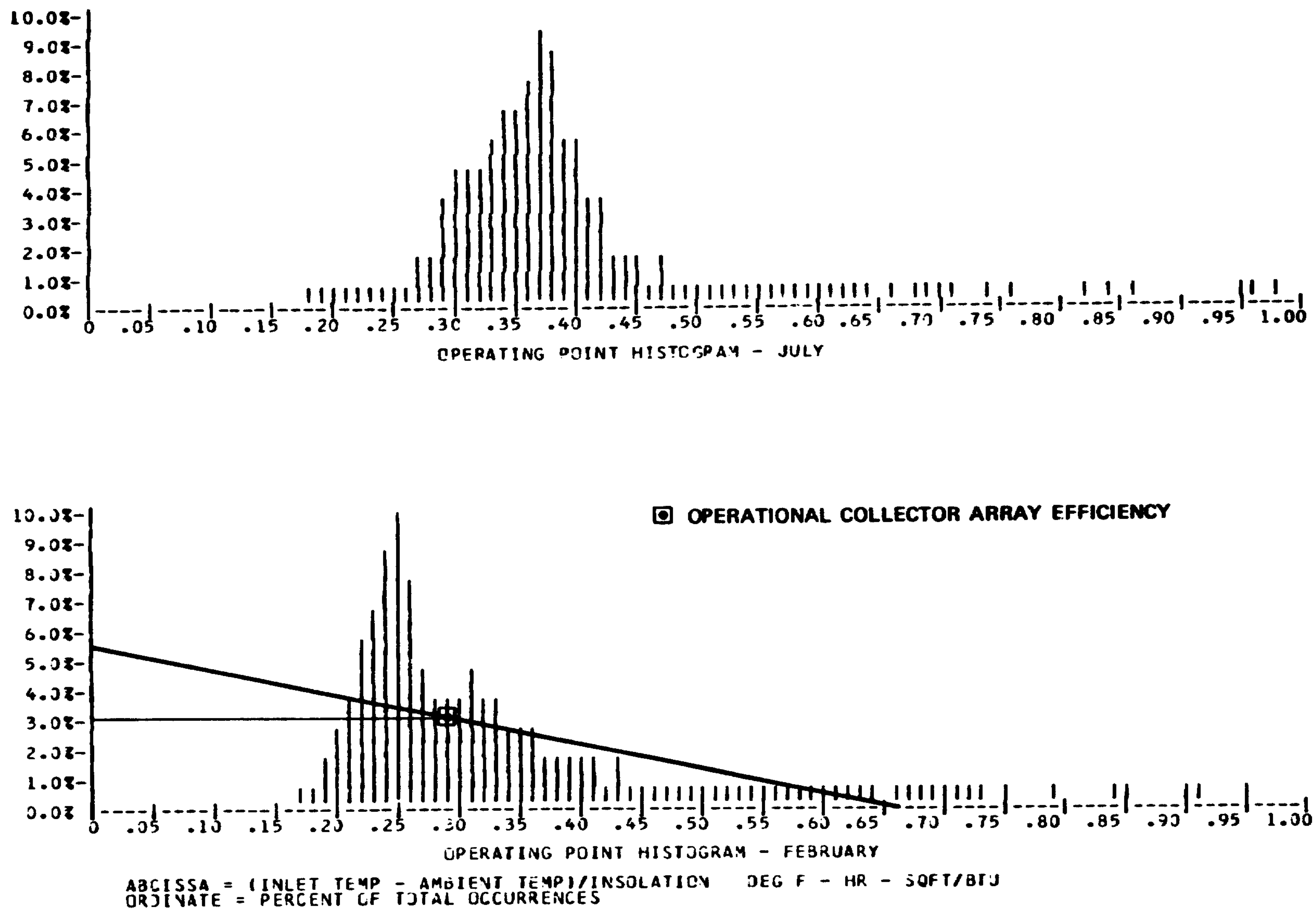


Figure 3.2.1-3 Colt Pueblo Operating Point Histograms for Typical Winter and Summer Months

3.2.2 Storage Subsystem

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

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

where:

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

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

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

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

Table 3.2.2-1 summarizes the storage subsystem performance during the report period. Temperature sensor T150 was biased low by approximately 0.7°F during the entire evaluation period. To enable a better assessment of storage performance, this temperature bias was added to T150 to estimate the actual energy flows to the liquid thermal storage subsystem.

During the twelve month period, a total of 66.08 million Btu was delivered to the storage tanks and a total of 56.16 million Btu was removed for support of system loads. The net change in stored energy during this same time period was 0.32 million Btu, which leads to a storage efficiency of 0.85 and a total energy loss from storage of 9.60 million Btu.

The computed storage efficiency of 0.85 is relatively high as compared to most solar energy systems. However, the average storage temperature during the period that efficiency was computed was only 109°F, so the high value of efficiency is not unrealistic. This is true because the potential for heat transfer becomes smaller as the differential temperature between the internal fluid and the external environment becomes smaller. However, this is not meant to detract in any way from the fact that the storage subsystem performed well during the reporting period. The system is well insulated and the effective heat transfer coefficient averaged only 26.76 Btu/Hr-°F during the period.

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

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

where

C = Effective storage heat transfer coefficient

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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)	Warehouse Temp (TA + 20°F)	Effective Storage Heat Loss Coefficient (Btu/Hr°F)
Feb 79	7.03	7.07	-.01	1.00	98	52	-0.97
Mar 79	8.20	8.35	-.08	1.01	99	62	-2.54
Apr 79	8.05	6.97	.25	0.90	107	71	32.02
May 79	6.09	5.51	-.21	0.87	110	76	31.23
Jun 79	5.90	2.90	.48	0.57	133	88	77.78
Jul 79	2.84	1.02	-.61	0.15	145	95	65.32
Aug 79	2.36	2.12	.30	1.02	95	93	-40.32
Sep 79	4.21	1.42	.34	0.42	120	85	97.22
Oct 79	3.17	2.32	-.29	0.64	106	79	36.75
Nov 79	7.09	7.70	-.09	1.07	103	53	-14.44
Dec 79	5.94	6.07	0	1.02	100	52	- 3.64
Jan 80	5.20	4.71	0.24	0.95	97	47	6.72
Total	66.08	56.16	0.32	--	--	--	--
Average	5.51	4.68	0.03	0.35	109	71	23.76

Q_{si} = Energy to storage

Q_{so} = Energy from storage

ΔQ = Change in stored energy

T_s = Storage average temperature

T_a = Average ambient tempeature in the vicinity of storage

t = Number of hours in the month

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [9]. It has been calculated for each month in this report period and included, along with an assumed warehouse average temperature, in Table 3.2.2-1.

Examination of the values for the effective storage heat transfer coefficient shows that the variation is quite significant. The storage heat loss is lowest during the coldest winter months and highest during the spring and fall. Overall, the heat loss coefficient is quite low which is indicative of a properly performing liquid storage system. The indicated storage gains during the winter months are probably due to the uncertainty associated with temperature T150 which affects the storage energy inlet parameter which in turn affects the energy balance of the subsystem.

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 Colt Pueblo 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 February 1979 through January 1980, the solar energy system supplied a total of 4.62 million Btu to the hot water load. The total hot water load for this period was 2.16 million Btu, and the weighted average monthly solar fraction was 79 percent.

The monthly average hot water load during the reporting period was 0.18 million Btu. This is based on an average daily consumption of 14 gallons, delivered at an average temperature of 116°F and supplied to the system at an average temperature of 61°F. The temperature of the supply water ranged from a low of 49°F in February to a high of 74°F in July and August.

Each month an average of 0.39 million Btu of solar energy and 0.56 million Btu of auxiliary thermal (electrical) energy were supplied to the hot water subsystem. Since the average monthly hot water load was 0.18 million Btu, an average of 0.77 million Btu (total of 9.19 million Btu) was lost from the hot water tank each month. These high losses are attributable to the very low hot water demand and a high preheat tank loss coefficient.

TABLE 3.2.3-1
HOT WATER SUBSYSTEM PERFORMANCE

Month	Hot Water Parameters				Energy Consumed (Million Btu)			Weighted Solar Fraction (Percent)
	Load (Million Btu	Gallons Used	Temperatures (°F)		Solar	Auxiliary Thermal	Auxiliary	
			Supply	Delivery				
Feb 79	0.18	395	49	105	0.14	1.28	1.28	43
Mar 79	0.28	641	53	104	0.39	0.51	0.51	69
Apr 79	0.25	530	57	113	0.54	0.18	0.18	90
May 79	0.26	617	64	113	0.55	0.04	0.04	93
Jun 79	0.21	409	73	135	0.53	0.01	0.01	100
Jul 79	0.25	489	74	147	0.52	0.01	0.01	98
Aug 79	0.15	532	74	108	0.79	0.08	0.08	72
Sep 79	0.24*	616*	71*	120*	0.38	0.00	0.00	100*
Oct 79	0.13	353	68	112	0.28	0.23	0.23	82
Nov 79	0.11	237	56	110	0.26	1.42	1.42	37
Dec 79	0.05	110	51	116	0.15	1.46	1.46	31
Jan 80	0.05	101	51	112	0.09	1.51	1.51	15
Total	2.16	5,030	--	--	4.62	6.73	6.73	--
Average	0.18	419.2	61	116	0.39	0.56	0.56	79**

*Estimate from only 11 days out of the month.

$$\text{**Weighted solar fraction} = \frac{\sum_{1}^{12} HWSFR_i \times HWL_i}{HWL}$$

where HWL = Hot Water Load
HWSFR = Hot Water Solar Fraction

The contractor predicted hot water subsystem performance, based on an expected 10 gallon per day hot water flow, was a heating demand of 0.4 million Btu per month and a solar fraction of 25 percent. Thus, the reduced heating load (lower DHW outlet temperatures) resulted in an increased solar fraction for the hot water subsystem.

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 Colt Pueblo space heating subsystem is presented in Table 3.2.4-1. For the 12 month period from February 1979 through January 1980, the solar energy system supplied a total of 51.52 million Btu to the space heating load. The total heating load for this period was 168.62 million Btu, and the average monthly solar fraction was thirty-one percent. The collector contractor estimated that the solar system would supply enough solar energy to satisfy 34 percent of the heating demand. The actual results indicate suitable agreement.

It must be emphasized that all values presented in this section relating to the performance of the space heating subsystem are based on measured parameters. In other words the space heating load, solar contribution and auxiliary thermal energy used are all determined based on the measured output of the space heating subsystem. These measured values do not include any of the various solar energy losses that are present in the system. However, solar energy losses are generally added to the interior of the building and, as such, represent an uncontrolled (unmeasured) contribution to the space heating load. At the Colt Pueblo site these solar energy losses occur during energy transport between the various subsystems and, to a lesser extent, from the storage tank and the domestic hot water tank. However, these subsystems are located outside the heated space in the warehouse. Thus, no direct uncontrolled energy contribution can occur. These energy contributions may contribute to heating the warehouse, which in turn could reduce energy losses from the heated space.

TABLE 3.2.4-1

HEATING SUBSYSTEM PERFORMANCE

Month	Heating Parameters			Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
	Load (Million Btu)	Temperatures (°F)					
		Building	Outdoor	Solar	Auxiliary Thermal	Auxiliary	
Feb 79	29.41	76	32	6.93	22.48	40.88	24
Mar 79	24.36	76	42	7.96	16.37	34.83	33
Apr 79	14.31	76	51	6.43	7.96	20.40	44
May 79	8.98	75	56	4.96	4.03	12.58	55
Jun 79	3.64	77	68	2.36	1.27	3.92	65
Jul 79	0.77	77	75	0.50	0.28	0.85	64
Aug 79	2.51	80	73	1.34	1.11	2.36	56
Sep 79	3.08	76	65	1.03	2.05	3.73	34
Oct 79	6.18	74	54	2.04	4.13	7.11	33
Nov 79	20.59	71	33	7.44	13.15	21.55	36
Dec 79	24.41	71	32	5.91	18.55	28.11	24
Jan 80	30.25	68	27	4.62	25.56	36.00	16
Total	168.62	--	--	51.52	116.94	212.32	--
Average	14.05	75	51	4.29	9.75	17.69	31 *

*Measured average solar fraction is weighted by load.

During the primary heating season (February 1979 through April 1979) and October 1979 through January 1980, a total of approximately 18.36 million Btu of solar energy was added to the warehouse through these various losses. This amount of uncontrolled solar energy is thirty three percent of the total solar energy delivered to meet the heating demands.

Figure 3 2.4-1 illustrates the measured building heat loss coefficient (UA) determined by ratioing the actual measured monthly space heating load to the monthly heating degree-days multiplied by 24. The UA oscillates about an average of 1200 Btu/Hr°F for the first heating season October 1978 through May 1979. The UA for the beginning of the next heating season October 1979 through January 1980 is somewhat lower. This is attributed to increased insulation of the heated space and to removal of a portion of the heated space by reducing thermostats and closing doors which occurred in December 1979.

During the 12 month reporting period a total of 212.32 million Btu of auxiliary energy was consumed by the space heating subsystem in order to supply 116.94 million Btu of thermal energy to supplement solar energy. Using a conversion factor of 91,500 Btu per gallon, approximately 2320 gallons of propane were needed to support the space heating subsystem.

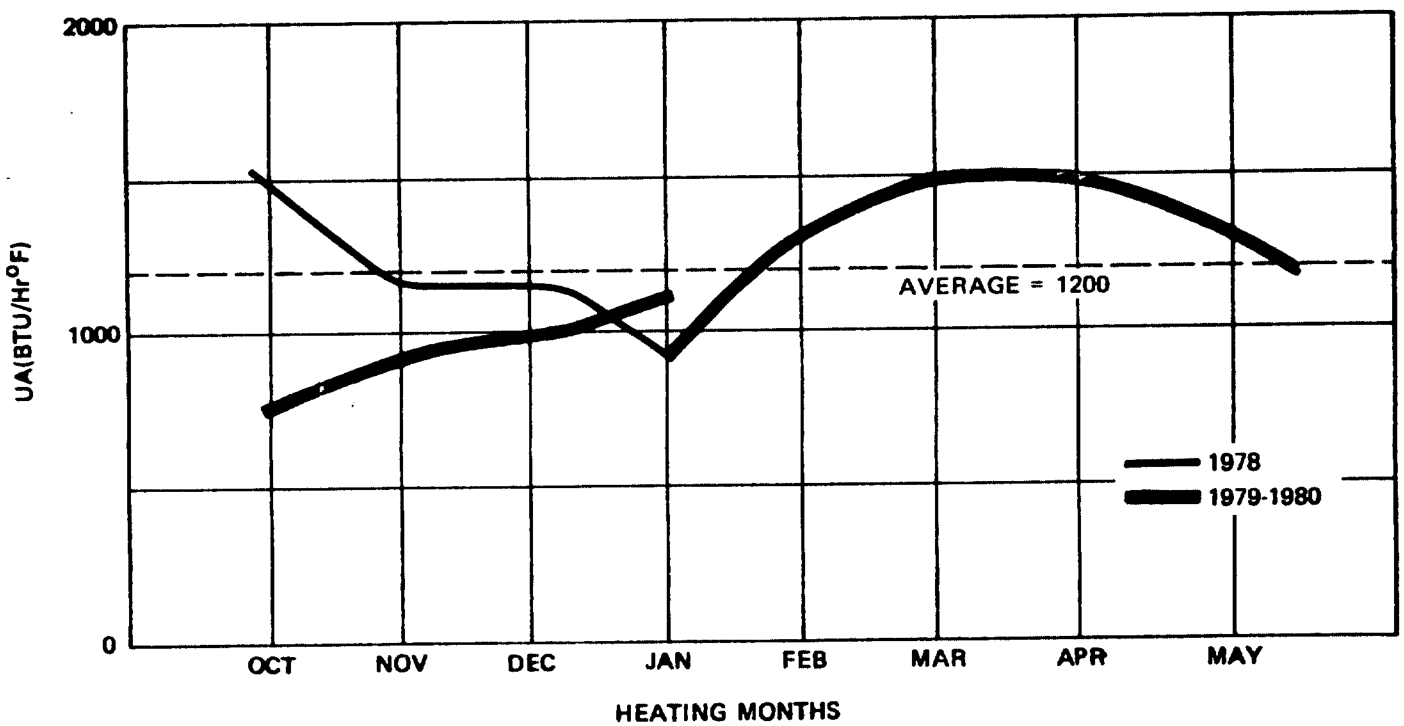

Figure 3.2.4-1 Building Heat Loss Coefficient

4. OPERATING ENERGY

Operating energy for the Colt Pueblo Solar Energy System is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy, hot water subsystem operating energy and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Also included in the Total Operating energy is the heat type freeze protection energy requirements although this energy does contribute thermal energy to the system. Measured monthly values for subsystem operating energy are presented in Table 4-1.

Total system operating energy for the Colt Pueblo Solar Energy System is that electrical energy required to operate the pumps in the energy transport subsystem and the tape energy required to prevent freezing. These are shown as EP100, EP301, EP400, and EP302, respectively, in Figure 2-1. Although additional electrical energy is required to operate the valves in the energy transport subsystem and the control system for the installation, it is not included in this report. These devices are not monitored for power consumption and the power they consume is inconsequential when compared to the pump motor powers and heat tape power.

During the 12 month reporting period, a total of 25.92 million Btu (7595 kWh) of operating energy was consumed. However, this includes the energy required to operate the blower in the auxiliary furnace, and that energy would be required whether or not the solar energy system was being utilized for space heating. Therefore, the energy consumed by the auxiliary furnace blower is not considered to be solar peculiar operating energy, even though it is included as part of the space heating subsystem operating energy.

TABLE 4-1

OPERATING ENERGY

Month	Solar ECSS Operating Energy (Million Btu)	Space Heating Solar Operating Energy (Million Btu)	Hot Water Heating Solar Operating Energy (Million Btu)	Total System Solar Operating Energy (Million Btu)	Space Heating Circulating Fan Energy (Million Btu)	Heat Tape Energy (Million Btu)	Total System Operating Energy (Million Btu)
Feb 79	0.54	0.36	0.002	0.90	2.54	1.35	4.80
Mar 79	0.62	0.43	0.023	1.07	1.75	0.50	3.32
Apr 79	0.65	0.30	0.046	1.00	1.09	0.18	2.27
May 79	0.55	0.21	0.053	0.81	0.70	0.00	1.51
Jun 79	0.58	0.06	0.036	0.68	0.17	0.00	0.85
Jul 79	0.35	0.02	0.050	0.42	0.69	0.00	1.11
Aug 79	0.20	0.04	0.031	0.27	0.08	0.00	0.35
Sep 79	0.40	0.02	0.023	0.44	0.49	0.00	0.93
Oct 79	0.25	0.06	0.018	0.33	0.27	0.20	0.80
Nov 79	0.58	0.31	0.015	0.91	0.81	1.64	3.36
Dec 79	0.50	0.24	0.009	0.75	0.92	1.60	3.27
Jan 80	0.49	0.20	0.007	0.70	0.99	1.66	3.35
Total	5.71	2.25	0.313	8.28	10.50	7.13	25.92
Average	0.48	0.19	0.026	0.69	0.88	0.59	2.16

A total of 8.28 million Btu (2426 kWh) of operating energy was required to support the pumps that are unique to the solar energy system during the reporting period. Of this total, 5.71 million Btu were allocated to the Energy Collection and Storage Subsystem (ECSS), 2.25 million Btu were allocated to the solar portion of the Space Heating Subsystem, and 0.31 million Btu were allocated to the Hot Water Subsystem. 10.50 million Btu was allocated to space heating circulating fan and 7.13 million Btu was consumed by the heat tapes. However, these additional energies are included in the total system operating energy. The meaningful operating energy for the solar energy system is 15.41 million Btu, and includes the 8.28 million Btu total system operating energy and the 7.13 million Btu heat tape operating energy. Since a measured 56.14 million Btu of solar energy was delivered to system loads during the reporting period, a total of 0.27 million Btu (80 kWh) of operating energy was required for each one million Btu of solar energy delivered to the system loads.

5. ENERGY SAVINGS

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

The Colt-Pueblo Solar Energy System has a gas fired propane furnace for auxiliary space heating and auxiliary energy for water heating is provided by electricity. For computational purposes the gas furnace is considered to be 60 percent efficient and the electrical hot water heating element is considered to be 100 percent efficient. A small amount of thermal energy is delivered thermally to space heating and hot water subsystems, from the heat tapes. Energy savings for the 12 month reporting period are presented in Table 5-1. During this time the system realized a gross electrical energy savings of 4.63 million Btu, which is the amount of solar energy supplied to the hot water subsystem. However, a total of 15.41 million Btu of electrical operating energy was required to support the solar energy system, so the net electrical energy cost was 10.78 million Btu, or 3159 kWh. Fossil fuel savings for the reporting period totaled 106.24 million Btu, or 1161 gallons of propane (based on a heating value of 91,500 Btu per gallon). The total savings in fossil equivalent at source of energy generation, considering the 30 percent average efficiency in generating electrical energy and delivering it from source to load, was 70.31 million Btu, or 768 gallons of propane. The large reduction in fossil savings is due to the cost of operating the solar system and to the heat tape energy requirements necessary to prevent energy transport piping freezes.

TABLE 5-1
ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu) Hot Water	Fossil Energy Savings (Million Btu) Space Heating	Solar Operating Energy Plus Heat Tape Energy (Million Btu)	Net Savings			Total Savings* Fossil Equivalent At Source (Million Btu)	Total Savings Gallons of Propane
				Electrical		Fossil		
				Million Btu	kWh	Million Btu		
Feb 79	0.14	12.59	2.25	-2.11	-618.2	12.59	5.56	60.7
Mar 79	0.39	16.94	1.57	-1.18	-345.7	16.94	13.01	142.2
Apr 79	0.54	16.49	1.18	-0.64	-187.5	16.49	14.36	156.9
May 79	0.55	15.50	0.81	-0.26	- 76.2	15.50	14.63	159.9
Jun 79	0.54	7.27	0.68	-0.14	- 41.0	7.27	6.80	74.4
Jul 79	0.52	1.54	0.42	0.10	2.9	1.54	1.57	17.2
Aug 79	0.78	2.85	0.27	0.51	149.4	2.85	4.55	49.7
Sep 79	0.38	1.87	0.44	-0.06	- 17.6	1.87	1.67	18.3
Oct 79	0.28	3.52	0.53	-0.25	- 73.3	3.52	2.69	29.4
Nov 79	0.27	12.20	2.55	-2.28	-668.0	12.20	4.60	50.3
Dec 79	0.15	8.96	2.35	-2.20	-644.6	8.96	1.63	17.8
Jan 80	0.09	6.51	2.36	-2.27	-665.1	6.51	-1.06	-11.6
Total	4.63	106.24	15.41	-10.78	-3184.9	106.24	70.31	765.2
Average	0.39	8.85	1.28	-0.90	-265.41	8.85	5.86	63.8

*Total Savings Fossil Equivalent = Fossil savings + $\frac{\text{(electrical savings - solar operating energy)}}{0.3}$

6. MAINTENANCE

A considerable amount of maintenance was required at the Colt Pueblo site since activation.

The thermal storage tank was unsealed and the insulation ineffective (wet) until November, 1978, when the storage tank subsystem was repaired.

In January, 1979, a solar space subsystem malfunction and cold localized ambient temperatures associated with the DHW water lines caused water line breakage. The water transport supply lines were repaired in early February 1979.

In February, 1979, the solar storage water pumps were reactivated by replacing fuses in the main circuit. In addition, the solar storage tank insulation was again repaired.

In March, 1979, a new DHW controller was installed which significantly improved that subsystem's performance.

In August, 1979, a leak in the solar storage tank was repaired.

In January, 1980, a solar space subsystem malfunction caused the water-to-air heat exchanger coils to freeze.

The solar space subsystem was repaired and returned to operation on April 11, 1980.

7. SUMMARY AND CONCLUSIONS

During the 12 month reporting period, the measured daily average incident insolation in the plane of the collector array was 1,681 Btu/Ft^2. This was ten percent below the long-term daily average of 1,859 Btu/Ft^2. The measured insolation appears to be an accurate representation of the long-term average for the area. Both the long-term averages for ambient temperature and insolation are derived from data taken at the Pueblo, Colorado airport. During the period from September, 1979, through January, 1980, the measured average outdoor ambient temperature was 51°F. This was two degrees below the long-term average of 53°F for the same period. As a result 5,823 heating degree-days were accumulated, as compared to the long-term average of 5,394 heating degree-days.

The solar energy system satisfied 31 percent of the total measured load (hot water plus space heating) during the 12 month reporting period. This was slightly below the design value of 34 percent estimated by Colt, Inc. [1]. The reduction in overall system solar fraction was due primarily to the measured performance of the space heating subsystem. The space heating solar fraction for the reporting period was 31 percent. However, the computations do not account for uncontrolled losses of solar energy into the building that result primarily from transport piping losses. As discussed in Section 3.2.4, these losses are substantial and provide a considerable reduction in the measured space heating load.

A total of 357.33 million Btu of incident solar energy was measured in the plane of the collector array during the reporting period. The system collected 74.48 millio Btu of the available energy, which represents a collector array efficiency of 21 percent. During periods when the collector array was active, a total of 242.63 million Btu was measured in the plane of the collector array. Therefore, the operational collector efficiency was 31 percent. Taking into account the heat exchanger penalty factor, the collector array performance was close to that expected.

During the reporting period, a total of 66.08 million Btu of solar energy was delivered to the storage tanks. During this same time period 56.16 million Btu were removed from storage for support of the domestic hot water and space heating loads. The majority of this (51.52 million Btu) went to the space heating subsystem and the remainder was used in support of the domestic hot water subsystem. The effective storage heat loss coefficient was 23.76 Btu/Hr-°F, which is low and indicates a well insulated storage subsystem. The average temperature of storage was 109°F for the period.

The hot water load for the 12 month reporting period was 2.16 million Btu. A total of 4.62 million Btu of solar energy and 6.73 million Btu of auxiliary energy were supplied to the subsystem, which represents a weighted hot water solar fraction of 79 percent. The average daily consumption of hot water was 14 gallons, delivered at an average temperature of 116°F. A total of 9.19 million Btu was lost from the hot water tank during the reporting period. This large loss is due to the low domestic hot water consumption, large heat loss coefficient associated with domestic hot water storage tank and the low temperatures associated with an unheated warehouse.

The measured space heating load was 168.62 million Btu for the reporting period. The heating solar fraction for the 12 month period was thirty one percent. During the reporting period, a total of 51.52 million Btu of measured solar energy and 116.94 million Btu of auxiliary thermal energy were delivered to the space heating load, and this energy maintained an average building temperature of 75°F. The 116.94 million Btu of auxiliary thermal energy supplied to the space heating subsystem represents 212.32 million Btu, or 2320 gallons of propane that were required for support of the space heating load.

A total of 15.41 million Btu, or 4515 kWh, of electrical operating energy was required to support the solar energy system during the 12 month reporting period. This does not include the electrical energy required to operate the fan in the auxiliary furnace. This fan would be required for operation of the space heating subsystem regardless of the presence of the solar energy system.

Fossil energy savings for the 12 month reporting period were 106.24 million Btu (1161 gallons of propane) and gross electrical energy savings were 4.63 million Btu. However, when the 15.41 million Btu of electrical operating energy is taken into account, the net electrical energy costs were 10.78 million Btu, or 3185 kWh. If a 30 percent efficiency is assumed for power generation and distribution, then the net electrical energy cost translate into a cost of 35.93 million Btu in generating station fuel requirements. Thus, the overall equivalent fossil savings at the source of energy generation was 70.31 million Btu or 768 gallons of propane assuming a conversion factor of 91,500 Btu/gallon. It should also be noted that the fossil energy savings are based only on the measured amount of solar energy delivered to the space heating subsystem. As discussed in Section 3.2.4, the fossil energy savings will increase considerably if the uncontrolled solar energy input to the building is considered.

In general, the Colt-Pueblo Solar Energy System performed reasonably well during the reporting time period. The space heating subsystem solar energy met 31 percent of the measured space heating load which was close to the expected 34 percent solar fraction. Although the hot water solar fraction was 79 percent, the overall energy saving capability of this system was reduced because of the low hot water demand. However, it must be again stressed that the measured heating subsystem performance does not include the uncontrolled addition of solar energy to the building. If the uncontrolled losses could have been reduced to an inconsequential level, then the measured system performance would have improved considerably.

8. REFERENCES

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS

AND

SOLAR TERMS

APPENDIX A
DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

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

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

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

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

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the 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 auxiliary fossil fuel, and electrical auxiliary thermal energy, and the operating energy for the subsystem. In addition, the solar energy supplied to the subsystem, along with solar fraction is tabulated. The load of the subsystem is tabulated and used to compute the estimated electrical and fossil fuel savings of the subsystem. The load of the subsystem is further identified by tabulating the supply water temperature, and the outlet hot water temperature, and the total hot water consumption.

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

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

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

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to 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.
- AUXILIARY FOSSIL FUEL (HAF) is the amount of fossil energy supplied directly to the subsystem.
- FOSSIL ENERGY SAVINGS (HSVF) is the estimated difference between the fossil energy requirements of an alternative conventional system (carrying the full load) and the actual fossil energy required by the subsystem.

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

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

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

ENVIRONMENTAL SUMMARY

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

- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.

- WIND SPEED (WIND) is the average wind speed measured at the site.

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

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS

COLT PUEBLO

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR COLT-PUEBLO

I. INTRODUCTION

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

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

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

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

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

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

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

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

For a liquid system ΔH is generally given by

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

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

For an air system ΔH is generally given by

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

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

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

For electrical power, a general example is

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

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

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

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

II. PERFORMANCE EQUATIONS

The performance equations for Colt-Pueblo used for the data evaluation of this report are contained in the following pages and have been included for technical reference and information.

EQUATIONS USED IN MONTHLY PERFORMANCE ASSESSMENT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

AVERAGE AMBIENT TEMPERATURE (°F)

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

AVERAGE BUILDING TEMPERATURE (°F)

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

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

FOR ± 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)

$SECA = \Sigma\ [M100 \times CP46\ (0.5 \times (T101 + T151)) \times (T151 - T101)] \times \Delta\tau$

WHERE CP46 ( ) IS SPECIFIC HEAT OF COLLECTOR TO STORAGE ENERGY TRANSFER FLUID (SHELL 33).

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

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

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

SOLAR ENERGY TO STORAGE (BTU)

$$STEI = \Sigma\ [M100 \times CP46\ (0.5 \times (T100 + T150)) \times (T150 - T100)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE TO SPACE HEATING (BTU)

$$STEO1 = \Sigma\ [M400 \times HWD\ (T450, T400)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE TO HOT WATER (BTU)

$$STEO2 = \Sigma\ [M300 \times HWD\ (T350, T300)] \times \Delta\tau$$

SPACE HEATING TRANSPORT LOSSES (BTU)

$$TWH = TA + 20$$

$$AHL = 51.053 \times ((T400 + T450)/2 - TWH) * (0.21 + 5.E\text{-}4) \times TST)$$

SPACE HEATING HEAT TAPE GAIN

$$AHG = 11.95E0 \times (65 - TA)$$

HOT WATER TRANSPORT LOSSES

$$AHWL = 28.22 \times ((T352 + T350 + T300)/3 - TWH) \times (.21 + 5.E\text{-}4 \times TST)$$

HEAT TAPE ENERGY

$$HTAPE = 56.8833 \times \Sigma\ EP302 \times \Delta\tau$$

HOT WATER HEAT TAPE GAIN

$$AHWG = HEAT\ TAPE\ ENERGY$$

$$= -\ AHG$$

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

$$\mathrm{HWSVE} = \mathrm{HWSE} - \mathrm{HWOPE}$$

AUXILIARY FOSSIL FUEL (BTU)

$$\mathrm{HAF} = \mathrm{HCON} * (\mathrm{F400} - \mathrm{LF400})$$

WHERE HCON IS HEAT CONTENT OF THE FOSSIL FUEL

SPACE HEATING LOAD (BTU)

$$\mathrm{HL} = \mathrm{HAT} + \mathrm{HSE}$$

SPACE HEATING LOAD (BTU) USING AIR FLOW MEASUREMENTS IF T651 > T601 T652 > T602

$$\mathrm{HLA} = \Sigma\, [\mathrm{M601} \times \mathrm{HRF} \times (\mathrm{T651} - \mathrm{T601}) + \mathrm{M602} \times \mathrm{HRF} \times (\mathrm{T652} - \mathrm{T602})] \times \Delta\tau$$

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

$$\mathrm{HSFR} = 100 \times \mathrm{HSE}/\mathrm{HL}$$

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

$$\mathrm{HSVE} = \mathrm{HOPES}$$

SPACE SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

$$\mathrm{HSVF} = \mathrm{HSE}/\mathrm{HEFF}$$

SYSTEM LOAD (BTU)

$$\mathrm{SYSL} = \mathrm{HL} + \mathrm{HWL}$$

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

$$\mathrm{SFR} = (\mathrm{HL} \times \mathrm{HSFR} + \mathrm{HWL} \times \mathrm{HWSFR})/\mathrm{SYSL}$$

SYSTEM OPERATING ENERGY (BTU)

$$\mathrm{SYSOPE} = \mathrm{CSOPE} + \mathrm{HWOPE} + \mathrm{HOPE} + \mathrm{HTAPE}$$

WHERE HTAPE IS ELECTRICAL ENERGY TO THE LIQUID TRANSPORT SYSTEM HEAT TAPES

SOLAR ENERGY FROM STORAGE (BTU)

$$STEO = STEO1 + STEO2 - AHG + AHL$$

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TSTM = \Sigma\ [(T200 + T201 + T202)/3]\ \times\ \Delta\tau$$

$$TSTL = TSTM$$

$$TST = (1/60) \times TSTM$$

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

$$CSEO = STEO1 + STEO2 - AHG + AHL$$

ECSS OPERATING ENERGY (BTU)

$$CSOPE = 56.8833 \times \Sigma\ EP100\ \times \Delta\tau$$

SPACE HEATING SUBSYSTEM SOLAR OPERATING ENERGY (BTU)

$$HOPES = 56.8833 \times \Sigma\ EP400 \times \Delta\tau$$

HOT WATER CONSUMED (GALLONS)

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

HOT WATER LOAD (BTU)

$$HWL = \Sigma\ [M301 \times HWD\ (T351,\ T301)] \times \Delta\tau$$

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

$$HWSE = STEO2$$

SOLAR ENERGY FROM HOT WATER PREHEAT TANK

$$HWSE1 = \Sigma\ [M300 \times HWD\ (T352,\ T300)]\ \times\ \Delta\tau$$

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

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

HOT WATER SUBSYSTEM OPERATING ENERGY (BTU)

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

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HSE = STE01 - AHG + AHL$$

AUXILIARY FOSSIL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HAT = HCON \times HEFF \times (F400 - LF400)$$

WHERE HCON IS THE HEAT CONTENT OF THE FOSSIL FUEL AND HEFF IS THE CONVERSION EFFICIENCY

SPACE HEATING CIRCULATING FAN ENERGY (BTU)

$$HOPEA = 56.8833 \times \Sigma\ EP600 \times \Delta\tau$$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$$HOPE = HOPEA + HOPES$$

SUPPLY WATER TEMPERATURE (°F)

$$TSW = T301$$

HOT WATER TEMPERATURE (°F)

$$THW = T351$$

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 = $\dot{S}$ECA/SEA

CHANGE IN STORED ENERGY (BTU)

STECH1 = STOCAP x TSTL x CP (TSTL) x RHO (TSTL)

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 = HSE + HWSE

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

HEATING AUXILIARY ENERGY (BTU)

HAE = AHG

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

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HWAE + HAE

AUXILIARY FOSSIL ENERGY TO LOADS

AXF = HAF

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HWSVE - CSOPE - HTAPE

TOTAL FOSSIL ENERGY SAVINGS (BTU)

TSVF = HSVF

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXE + AXF + SECA

SYSTEM PERFORMANCE FACTOR

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

COOLING LOAD FOR INFORMATION ONLY

IF T651 < T601 AND T652 < T602

$$\text{LOAD} = \Sigma\,[\text{M601} \times \text{HRF} \times (\text{T601} - \text{T651}) + \text{M602} \times \text{HRF} \times (\text{T602} - \text{T652})] \times \Delta\tau$$

APPENDIX C

LONG TERM AVERAGE WEATHER CONDITIONS

APPENDIX C

LONG TERM AVERAGE WEATHER CONDITIONS

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

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

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

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

REFERENCES

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

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

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

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

TABLE C-1

SITE: COLT PUEBLO 0.

LOCATION: PUEBLO CO

ANALYST: K. SHENFISH

F-CHART DRIVE NO.: 51.

COLLECTOR TILT: 45.00 (DEGREES)

COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 38.28 (DEGREES)

RUN DATE: 04/21/80

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR	WIND
JAN	1419.	896.	0.63156	1.891	1694.	1082	0	30.	8
FEB	1976.	1172.	[illegible]	1.544	1811.	848	0	35.	8.5
MAR	2460.	1563.	[illegible]	1.242	1942.	775	0	40.	9.6
APR	3053.	1953.	[illegible]	0.993	1954.	405	6	52.	10.4
MAY	3472.	2164.	[illegible]	0.854	1848.	148	27	61.	9.7
JUN	3637.	2433.	[illegible]	0.794	1931.	28	199	71.	9.4
JUL	3543.	2312.	[illegible]	0.820	1896.	0	353	76.	8.7
AUG	3213.	2102.	[illegible]	0.933	1960.	0	295	75.	7.9
SEP	2672.	1781.	[illegible]	1.144	2036.	55	91	66.	7.9
OCT	2044.	1361.	[illegible]	1.453	1983.	335	10	55.	7.4
NOV	1524.	955.	[illegible]	1.786	1706.	726	0	41.	7.5
DEC	1293.	782.	0.60475	1.979	1547.	992	0	33.	7.9

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.

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