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Solar Energy System Performance Evaluation

ARATEX SERVICES, INC.
INDUSTRIAL LAUNDRY
Fresno, California
June through September, 1978

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U.S. Department of Energy

National Solar Heating and Cooling Demonstration Program

National Solar Data Program

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION.

ARATEX SERVICES, INCORPORATED,
INDUSTRIAL LAUNDRY,
FRESNO, CALIFORNIA,

JUNE THROUGH SEPTEMBER, 1978.

HENRY L. ARMSTRONG, PRINCIPAL AUTHOR
V. S. SOHONI, SOLAR ENERGY STUDIES MANAGER
LARRY J. MURPHY, IBM PROGRAM MANAGER

950 5778

IBM CORPORATION
150 SPARKMAN DRIVE
HUNTSVILLE, ALABAMA 35805

PREPARED FOR THE
DEPARTMENT OF ENERGY
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SECRETARY FOR
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UNDER CONTRACT EG-77-C-01-4049
H. JACKSON HALE, PROGRAM MANAGER

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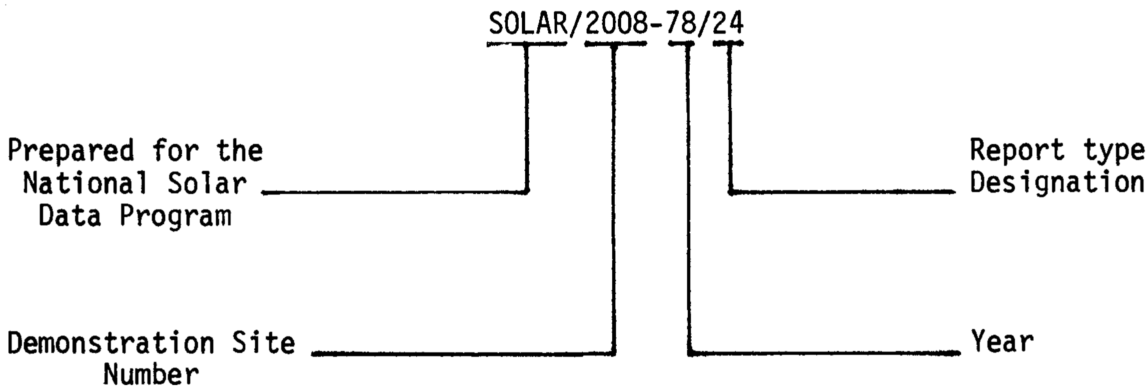
NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the ARATEX project site is designated as SOLAR/2008-78/24. The elements of this designation are explained in the following illustration:



- Demonstration Site Number:

  Each project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

- Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December)
  - Solar Energy System Performance Evaluations are designated by the number 14.*
  - Solar Project Descriptions are designated by the number 50
  - Solar Project Cost Reports are designated by the number 60

These reports are disseminated through the U. S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

*For sites which have two Solar Energy System Performance Evaluations in one calendar year, the number 24 is used to designate the second report.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy in accordance with the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to assist in establishment of a viable solar energy industry and to stimulate its growth so as to achieve a substantial reduction in fossil fuel consumption through widespread use of solar heating and cooling applications. The International Business Machines Corporation is contributing to this overall goal by monitoring, analyzing, and reporting system performance of solar energy systems through the National Solar Data Program. Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include topics such as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- System Performance Evaluation

All reports issued during this report period by the National Solar Data Program for the ARATEX Services Inc. industrial laundry solar energy system are listed in Section 6.

This System Performance Evaluation report is a product of the National Solar Data Program. Evaluation reports are periodically issued to document results from analysis of a specific solar energy system's operational performance during the period covered by the report. Information presented has been generated from data specific to the system being evaluated and includes system description, operational characteristics and capabilities, as well as evaluation of results from actual versus expected performance comparison. Each parametric value presented as characteristic of this system's performance represents over 8,000 discrete measurements obtained monthly through the National Solar Data Network.

Acknowledgments are extended to the personnel of ARATEX Services Inc. for their cooperation in the collection and analysis of their solar energy system's performance data.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report provides an operational summary of how the solar energy system installed at ARATEX Services Inc., an industrial laundry located in Fresno, California, performed during the report period June through September, 1978. This analysis is made by evaluation of measured system performance and by comparison of measured climatic data with long term average climatic conditions. Performance of major subsystems is also presented to illustrate their operation.

Measurement data used were collected [1-4]* by the National Solar Data Network (NSDN) [5] for the period June through September, 1978. System performance data are provided to the analyst through the NSDN via the IBM developed Central Data Processing System (CDPS) [6]. The CDPS supports the collection and analysis of solar data from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports on each site monitored. These monthly reports form a common basis for system evaluation and are the source of actual performance data used in this report.

Features of this report include: a brief system description, review of actual system performance during the report period, analysis of performance based on evaluation of climatic load and operational conditions, and an overall discussion of results.

Monthly values of average daily insolation and average ambient temperature measured at the ARATEX site are presented in Table 5.1-1. Also presented in the table are the long-term, average monthly values for these climatic parameters.

Long term insolation data are taken from the Climatic Atlas of the United States [7]. Other meteorological data are from the NOAA Local Climatological Data and site environmental data supplied by the IBM site instrumentation. Data contained in Table 5.1-1 clearly indicate that the average daily measured insolation is below the long-term average, and this has an adverse effect on solar collection.

The ARATEX solar system has an average hot water demand of over 30,000 gallons per day at a temperature of 180°F. In addition to the solar energy system, the laundry also has a heat recovery system which utilizes energy from the laundry's waste water to preheat the water entering the solar energy system. The heat recovery system reduced the hot water load at the laundry by 30 percent. Of the remaining load, 25 percent was provided by solar energy.

A high degree of overall system availability has been demonstrated by the ARATEX solar energy system. A complete discussion of availability is found in Section 5.5.

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* Numbers in brackets designate References found in Section 6.

The ARATEX system collected an average of 108 million Btu of solar energy per month during this report period. The available solar radiation was 83 percent of the long term average.

The collector array operational efficiency averaged 37 percent over the report period, which is less than the 60 percent efficiency expected for the operating conditions. This decrease in collector efficiency is attributed to array manifold losses and less than optimal collector flowrate. The collector array consists of 24 rows of collectors, totaling 140 collectors.

The actual fluid flowrate through the collectors is only 1.5 gallons per minute, but the expected flowrate is 2.5 gallons per minute. The collector array has been installed since August, 1977, and dirty covers may be contributing to the less than expected performance of the collector array.

The 12,500 gallon storage tank is well insulated and wrapped in corrugated aluminum; it is located above ground in a semi-enclosed area. The storage efficiency averaged 87 percent during the report period.

The ARATEX solar energy system has a dual circulating pump which forces water to flow between the collectors and storage. The energy required for collection and storage is simply the electrical power demanded by the pumps. For this report period, a total of 2.13 million Btu, or 639.53 kilowatt hours of energy was required to operate the collector pumps. This energy amounts to two percent of the average monthly value of collected solar energy.

Improvement in collector array performance can be realized by increasing the collector flowrate from 1.5 gallons per minute to 2.5 gallons per minute for each collector.

3. SYSTEM DESCRIPTION SUMMARY

The following is a brief summary of the ARATEX Services Inc. solar installation. For a detailed system description see Reference 8.

The system utilizes 140 collectors manufactured by Ying. The collectors are flat plate and lexan glazed. They provide an effective aperture area of 6500 square feet. The collectors are mounted in 24 rows on the flat roof of the building.

All collectors are connected in parallel with hoses and clamps to the copper manifold. The water is pumped between the collectors and the storage tank which is atmospherically vented. The 12,500 gallon insulated fiberglass storage tank is mounted on an above ground slab in a partially enclosed area.

All of the pumps for the system are located near the storage tank. All solar energy system piping is copper. All exterior piping is insulated with fiberglass covered by an aluminum jacket.

The solar energy system is used in conjunction with a heat recovery system. Softened cold water is first pumped through a heat exchanger which recovers heat from the laundry wastewater. The water then flows into the solar storage tank and circulates through the collectors. It is then pumped through another heat exchanger which boosts the water to the required temperature of 170°F. Steam from a low pressure gas-fired boiler located in the building is used as the auxiliary energy source.

The hot water is stored in a 4,000 gallon holding tank which contains an immersed heat exchanger that adds heat to the water from the steam condensate.

The collector to storage system is shown schematically in Figure 3-1. Figure 3-2 presents the storage to load schematic. ARATEX has three modes of operation. These modes of operation are described below.

<u>Mode 1 - Collector-to-Storage</u>: During this mode of operation, water is pumped from the 12,500 gallon storage tank through the collectors and back into the tank. This mode is initiated when the temperature of the collector outlet exceeds the storage tank temperature by 4.5°F and continues until this differential temperature drops below 1.5°F.

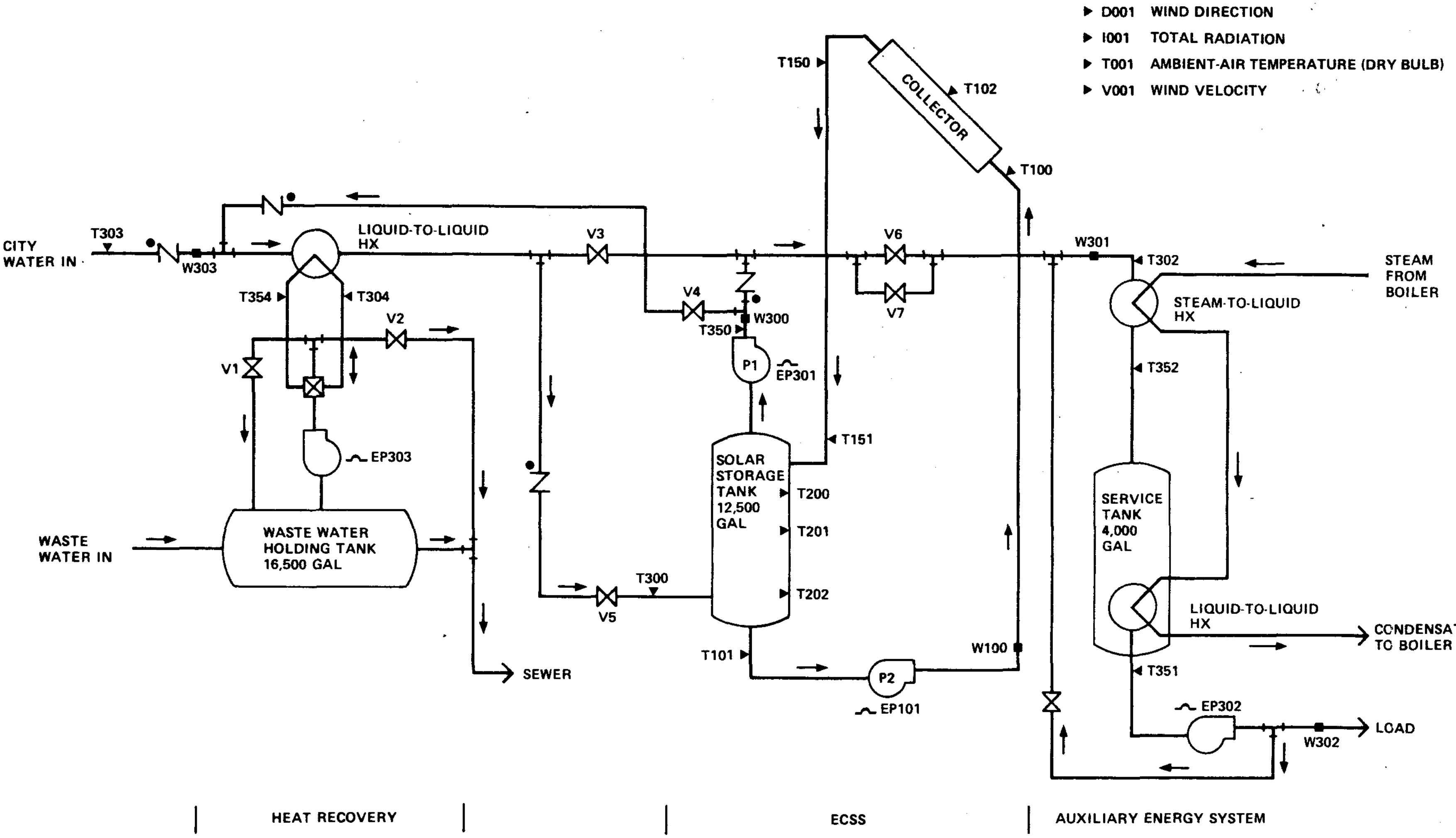

Figure 3-1. ARATEX Services Incorporated System Schematic Collector to Storage

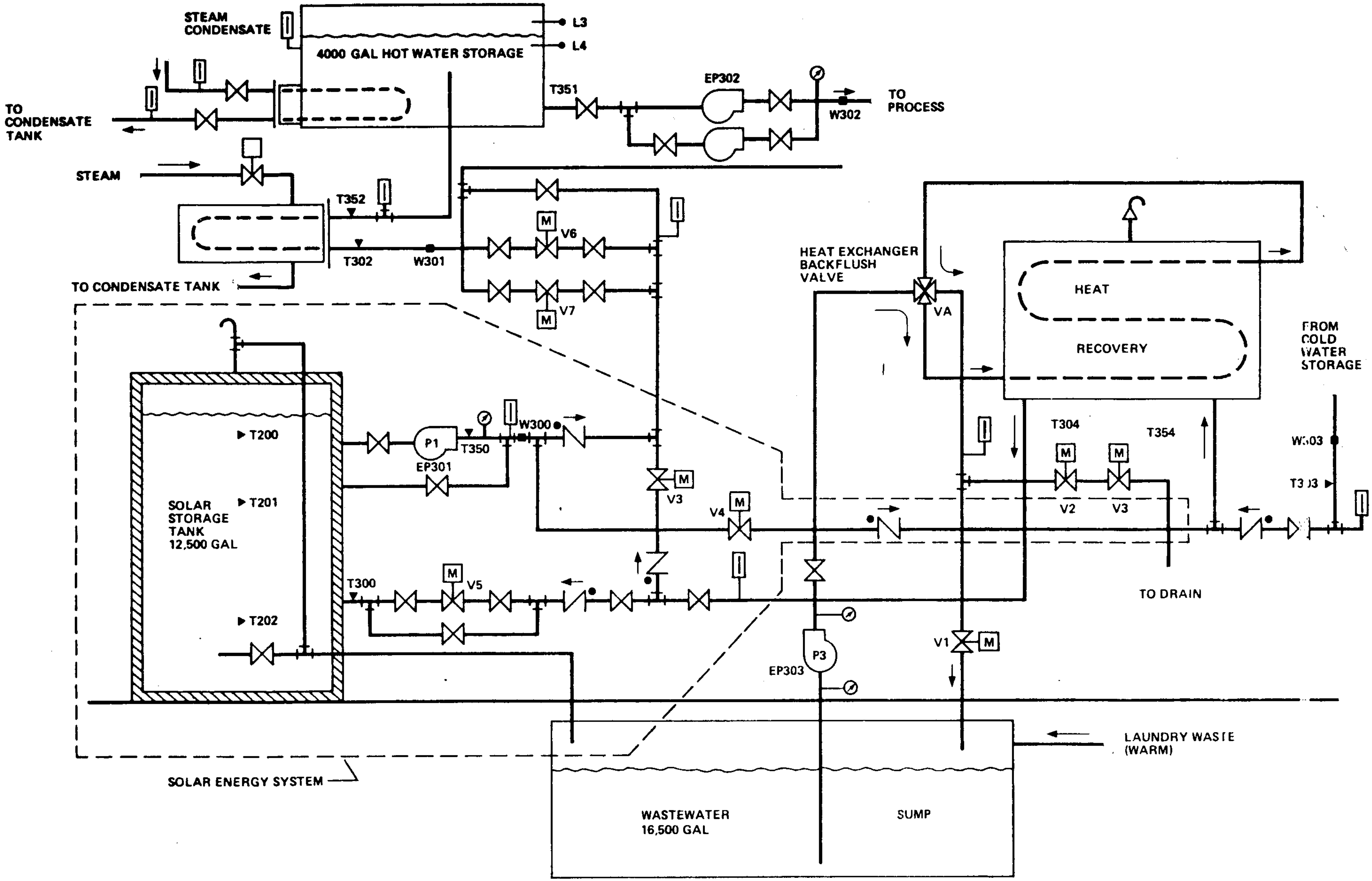

Figure 3-2. ARATEX Services Incorporated System Schematic Storage to Loads

Figure 3-3. Aerial Photograph of ARATEX Services Incorporated

Mode 2 - Hot Water Demand: This mode exists when there is a demand by the laundry for hot water. City water entering the system is preheated using the waste water in the 16,500 gallon holding tank. The temperature of the input city water is raised to approximately 115°F before being dumped into the 12,500 gallon storage tank. Then, as this water is withdrawn from the tank, it is pumped through a steam heat exchanger where auxiliary energy is added, as required, to maintain the water in the 4,000 gallon service tank at 180°F. Additional energy is also supplied in the service tank by extracting energy from the condensate line of the heat exchanger which passes through it.

Mode 3 - Storage-to-Waste Water: When the water in the 12,500 gallon, solar storage tank reaches 180°F, it is circulated by reverse flow through the waste water heat recovery system, thus storing any excess solar energy in the waste water tank. This mode is used to prevent damage to the 12,500 gallon fiberglass storage tank and enables the use of the waste water tank as a secondary solar storage tank.

4. PERFORMANCE EVALUATION TECHNIQUES

Measured solar energy system performance is provided by the CDPS through computation of solar energy performance factors. These computations are based on the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [11]. Because all solar energy systems are not identical, standard instrumentation equipment and software used in data processing is adapted to each system. The approach provides a standardized set of performance evaluation parameters for each solar system under consideration.

The National Solar Data Network equipment collects measurement data every five minutes at each site and stores it in an on-site memory. The data are retrieved periodically via standard voice grade telephone lines and data couplers, and stored on a master data base. They are then used to compute the primary performance factors.

Converted and tested data are first subjected to an hourly evaluation process. This process obtains all measurements for a particular hour, and performs the computations necessary to determine the hourly performance factors. These hourly calculations form the basis for subsequent daily and monthly system performance evaluation. Definitions of the performance factors are provided in Appendix A.

Monthly performance reports are generated to represent subsystem and total system performance. Monthly system summary reports are accompanied by a set of subsystem summaries which provide a record of performance for each day of the month. These monthly reports are the basis for actual system performance used in the comparisons presented in the subsequent sections of this report.

5. PERFORMANCE ASSESSMENT

The performance of the ARATEX solar energy system has been evaluated from June through September, 1978. Two perspectives have been utilized for this assessment. The first looks at the overall system view in which the total solar energy used by each subsystem and the percentage of each subsystem load provided by solar energy have been presented. The second presents a more in-depth look at the performance of the hot water subsystem. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details relating to the performance of the hot water subsystem. In addition, the total amount of energy consumed, both solar and auxiliary thermal, by the hot water system is provided.

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

5.1 Climatic Conditions

Monthly values of the total solar energy incident in the plane of the collector array and the average ambient temperature measured at the ARATEX site during the report period are presented in Table 5.1-1.

Also presented in Table 5.1-1 are long term average monthly values for these climatic parameters. Data for long term incident solar energy per unit area are estimates based on the Climatic Atlas of the United States [7]. These estimates use the horizontal data given in the reference to provide average values for the 30 degree angle from the horizontal of the ARATEX collector array. The estimation procedure is detailed in Reference [9]. All other long term, average climatic data were taken from the National Oceanic and Atmospheric Administration Summary [10].

The measured insolation deviated from the long term average by approximately 17 percent throughout the four month reporting period. The average measured ambient temperature was 4°F greater than the long term average. The low insolation has certainly had an adverse effect on the overall performance of the solar energy system.

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy applied to the system load. The total system load is the sum of the energy requirements, both solar and auxiliary thermal, for each subsystem. The portion of the total load provided by solar

TABLE 5.1-1

CLIMATIC CONDITIONS

Month	Incident Solar Energy Per Unit Area (30° Tilt) (Btu/Ft^2)		Ambient Temperature (°F)	
	Measured	Long Term Average	Measured	Long Term Average
Jun 78	61,679	68,588	76	73
Jul 78	62,192	69,483	83	81
Aug 78	62,191	68,943	81	79
Sep 78	52,948	63,620	73	73
Total	239,010	270,634	--	--
Average	59,753	67,659	78	77

energy is defined as the solar fraction of the load. This solar fraction is the measure of performance for the solar energy system when compared to design or expected solar contribution. The average monthly solar contribution to the load was 103 million Btu and the percent of the load supplied by the solar energy system ranged from 22 to 28 percent over the four months.

5.3 Subsystem Performance

The performance of solar energy subsystems is evaluated by calculating a set of primary performance factors based on those proposed in the inter-governmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [11]. Data from monitoring instrumentation, personalized to the unique features of the site's solar energy system, are collected via the National Solar Data Network. These data are first formed into factors which show the hourly performance of each subsystem by summation of averaging techniques. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each subsystem.

5.3.1 Collector Array Subsystem

Collector array performance is described by comparison of the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency, which may be expressed as

$$\eta_c = Q_s / Q_i$$

where:

η_c = Collector Array Efficiency (CAREF)

Q_s = Collected solar energy is the thermal energy removed from the collector array by energy transport medium (SECA)

Q_i = Incident solar energy is the total solar energy incident on gross collector array area (SEA)

The gross collector array area is 6,500 square feet. Measured monthly values of incident solar energy, collected solar energy, and collector array efficiency are presented in Table 5.3.1-1.

Evaluation of collector array efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yields operational collector efficiency. Operational collector efficiency, η_{co}, is computed as follows:

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

where:

Q_s = Collected Solar Energy (SECA)

TABLE 5.3.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Jun 78	403	99	.25	302	.33
Jul 78	410	117	.30	325	.36
Aug 78	410	122	.30	301	.41
Sep 78	346	95	.27	256	.37
Total	1569	433	-	1184	-
Average	392	108	.28	296	.37

Q_{oi} = Operational Incident Energy is the amount of solar energy incident on the collector array during the time that the collector loop is operating and attempting to collect energy (SEOP)

A_p = Gross Collector Area (product of the number of collectors and the total area of the envelope of one unit) (GCA)

A_a = Gross Collector Array Area (total area perpendicular to the solar flux vector including all mounting, connecting and transport hardware) (GCAA)

This latter efficiency term is not precisely the same as collector efficiency as represented by the ASHAE Standard 93-77 [13]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the collector operational efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are also presented in Table 5.3.1-1.

Table 5.3.1-1 shows that the average operational efficiency of the ARATEX collectors during the reporting period was 0.37. This value is somewhat less than expected based on manufacturer's data. There are several possible reasons for this. First, the collector fluid flow rate is only 1.5 gallons per minute through each collector, while the optimal flowrate is 2.5 gallons per minute. Secondly, communication with the manufacturer indicates the collectors may be dirty. The collectors should be washed several times per month. Furthermore, the collector efficiency is lower due to the higher temperature of the fluid from the heat recovery system, i.e., collector fluid inlet temperature.

5.3.2 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. This relationship is expressed by the equation:

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

where:

η_s = Storage efficiency is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage (STEFF)

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

TABLE 5.3.2-1

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)
Jun 78	99.00	99.00	10.70	1.10	143
Jul 78	117.00	113.00	0.09	0.97	144
Aug 78	121.95	108.73	3.97	0.92	142
Sep 78	94.78	86.13	0.70	0.92	139
Total	432.73	406.86	15.46	-	-
Average	108.18	101.72	3.87	0.98	142

Q_{so} = Energy from storage is the amount of energy extracted by the load subsystems from the primary storage medium (STEO)

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

Measured monthly values of energy to storage, energy from storage, change in stored energy, and storage efficiency are presented in Table 5.3.2-1.

The solar energy storage tank at ARATEX is 12 feet in diameter and 14 feet high. The top and sides of the tank are insulated with three inches of urethane and the bottom with one inch of urethane. The insulation is not waterproofed since the tank is in a covered area. The sides of the tank are sheathed with corrugated aluminum to prevent mechanical damage to the insulation. The storage tank performance was evaluated by determining the efficiency of the tank in utilizing the solar energy delivered to the tank and also by determining the tank heat loss coefficient.

The efficiency of the storage tank is based on the thermal energy in the tank which is available to satisfy the load as compared to the energy delivered to the tank. The thermal losses from the tank (energy which is not available to satisfy the load) are derived by comparing the energy delivered to the tank with the energy extracted from the tank and the change in stored energy. The ratio of the energy delivered to the tank minus the tank losses to the energy delivered to the tank is defined as the storage efficiency. The storage efficiency, the energy delivered to storage, the energy extracted from storage, the change in storage energy, and the average storage temperature are presented in Table 5.3.2-1 for each month of the evaluation period. The storage tank efficiency averaged 98 percent which indicates that the tank is effectively retaining the solar energy delivered to the tank. This is as expected because the energy collection and utilization are roughly in phase and the energy is withdrawn from the tank as fast as it is deposited because of the high rate of hot water consumption.

During the evaluation of the storage tank, it was discovered that when no energy was being delivered or extracted from the tank, the decay in temperature of the bottom portion of the tank was approximately eight times as rapid as the decay of the top and middle of the tank, even though the bottom of the tank was cooler than the remainder of the tank. Based on this observation, the tank was divided into two sections for thermal analysis and the heat loss coefficients were determined for each section. For simplicity, it was assumed that the two sections are thermally isolated. The heat loss coefficients are based on data collected on August 20, 1978 since it provided approximately 22 hours of no-flow conditions. The sink temperature for the upper section of the tank was based on measured data while the sink temperature from the lower section was approximated using an estimated earth temperature and the measured ambient temperature. The analysis determined that the R-values were 11 and 4 for the top and bottom sections, respectively. Based on the insulation thickness, the top and sides of the tank should provide an R-value of 17, while the bottom insulation should provide an R-value

TABLE 5.3.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Load Without Heat Recovery System (Million Btu)	Heat Recovery Energy (Million Btu)	Load With Heat Recovery System (Million Btu)	Solar Energy to Load (Million Btu)	Auxiliary Energy to Load (Million Btu)	Solar Fraction	Fossil Savings (Million Btu)
Jun 78	601	190	411	99	303	24	164
Jul 78	580	172	408	113	285	28	189
Aug 78	631	197	434	110	318	25	184
Sep 78	595	175	420	91	325	22	151
Total	2407	734	1673	413	1231	-	688
Average	602	184	418	103	308	25	172

of 6. During the period used for determining the loss coefficients, the temperature of the tank approached 180°F; however, the average temperature of the tank is generally closer to 130°F. Because of this temperature difference, the long-term R-values could be approximately 20 percent higher than those previously computed, because the insulation properties of urethane are highly dependent on temperature [14].

5.3.3 Hot Water Subsystem Performance

Hot water for the laundry is produced by first passing the city supplied cold water through a heat exchanger where the hot waste water from the laundry is used to heat the cold water. Next, this preheated water is then delivered to the solar storage tank where solar energy is added when it is available. The water is then drawn as needed from solar storage, and auxiliary energy is added as needed to raise the water temperature to approximately 180°F. The heated water enters a 4,000 gallon holding tank where it continues to recirculate through a steam heat exchanger to ensure hot water is available when needed by the laundry.

The hot water consumption is in excess of 30,000 gallons per work day. The normal demand period for hot water is 8 hours per day for five days per week. On weekends and holidays, the system operates only to collect and store solar energy.

Table 5.3.3-1 summarizes the most significant system performance parameters for this report period. The data presented in this table are taken from the monthly performance reports except where noted. The load without the heat recovery system is the load that would have existed had not the heat recovery system been in place. The heat recovery energy is the amount of energy conserved by the use of the heat recovery system. Table 5.3.3-1 shows that the use of the heat recovery system has effectively reduced the load by approximately 184 million Btu per month. As a result the laundry thermal load is reduced to an average of 418 million Btu per month, of which solar energy satisfied 25 percent. The use of solar energy has resulted in an average savings of 172 million Btu of fossil energy per month. The savings are computed based on an assumed 60 percent efficiency for a conventional fossil fuel boiler.

5.4 Operating Energy

Operating energy is defined as the energy used to provide for the transport of solar energy to the point of use. Total operating energy for the solar energy system at ARATEX consists of energy collection and storage subsystem operating energy (electrical energy required to support the ECSS heat transfer loops) and hot water operating energy (amount of electrical energy required to support the subsystem, i.e., fans and pumps which do not affect the thermal state of the subsystem). Measurements of the monthly values of these performance factors are presented in Table 5.4-1.

The average monthly operating energy for the solar energy system at ARATEX from June 1978 to September 1978 was 13.78 million Btu. This provided for the collection and storage of 108 million Btu/month of solar energy and the delivery of 103 million Btu/month to the hot water subsystem.

TABLE 5.4-1

OPERATING ENERGY (Million Btu)	
Jun	13.52
Jul	13.85
Aug	14.82
Sep	12.91
Total	55.10
Average	13.78

5.5 System Availability

The availability of a solar energy system is determined by the ability of its functional subsystems to perform their designed tasks when design operational conditions exist.

This may be expressed as:

$$\text{Availability} = \frac{\text{Solar Subsystem Equipment Operating Time}}{\text{Demand for Subsystem Time.}}$$

where:

Availability = 100 percent if the Demand Time is zero.

A subsystem is considered unavailable if a demand for its function exists, prevailing conditions meet appropriate prescribed criteria, and the subsystem fails to perform its function. A subsystem is then considered available at all times it is not unavailable. Availability also indicates the degree to which a subsystem responds to those demands which it was intended to satisfy. Subsystem availability alone, rather than total system availability, is presented in this report as more than one subsystem could be expected to be operational at the same time and a composite availability factor would confuse the actual conditions of performance. Availability of the ARATEX solar energy system as presented in this report is represented by the availability of its energy collection and storage subsystem and the solar fraction of the hot water subsystem. The monthly availability of the solar portions of these subsystems is presented in Table 5.5-1.

TABLE 5.5-1

SYSTEM AVAILABILITY BY MAJOR SUBSYSTEM

Month	Energy Collection and Storage Subsystem (Percent)	Hot Water Subsystem (Percent)
Jun 78	100	100
Jul 78	97	100
Aug 78	94	100
Sep 78	83	100
Average	94	100

The ARATEX energy collection and storage subsystem is considered available except for those times when the following conditions exist:

(1) Incident solar energy (total solar energy incident on the gross collector array) is less than 25 percent of its monthly average,

(2) Storage average temperature (mass-weighted average temperature of the primary storage medium) is less than its maximum allowable value, and

(3) Operational incident energy (solar energy incident on the collector array during the time that the collector loop is active) is less than 25 percent of the incident solar energy.

The average energy collection and storage subsystem availability for the ARATEX solar energy system was 94 percent for the period June through September, 1978. This is shown in Table 5.5-1.

The hot water subsystem availability has been determined strictly on the solar energy available to supply the load. For this reporting period, solar energy has always been available for delivery to the system load. Since there are no known failures present in the hot water subsystem, the hot water subsystem is considered to have been available 100 percent of the time.

5.6 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet hot water demands rather than energy provided by auxiliary fuel sources. The conventional source of hot water has been taken to be the baseline system with savings being realized whenever solar energy could be employed to supplant its use. Measured monthly values of fossil energy savings (estimated difference between fossil energy requirements of the alternative conventional system carrying the full load and the actual fossil energy consumed by the system) are presented in Table 5.6-1. The energy collection and storage subsystem operating energy (electrical energy to support the subsystem, such as fans and pumps, not intended to directly effect the thermal state of the subsystem) is reprinted here from Table 5.4-1 since this quantity is not included in the subsystem energy savings and must be algebraically added to obtain the total savings.

The value of 3,413 Btu/kilowatt hour has been used to convert all electrical energy savings to kilowatt hours and 1,000 Btu/cubic foot has been used to convert the fossil savings to cubic feet. A conventional boiler with a burner efficiency of 60 percent has been assumed.

The ECSS operating energy has averaged two percent of the collected solar energy throughout the reporting period. Hot water operating energy includes the electrical energy supplied for subsystem controls and the supply pump. Neither of these electrical power consumptions have been included in the saving calculations and thus must be algebraically added to obtain total savings.

Net savings have been realized every month throughout the reporting period. Monthly savings have increased in direct proportion to the solar fraction which is tabulated in Table 5.6-1. The 623.1 million Btu of total energy savings for the months of June through September, 1978 represents approximately 38 percent of the total hot water load during those months.

TABLE 5.6-1

ENERGY SAVINGS

Month	ECSS Operating Energy (Million Btu)	Hot Water Operating Energy (Million Btu)	Hot Water Fossil Savings (Million Btu)	Total Electric Savings (kw Hrs)	Total Fossil Savings (cubic feet)	Total Savings (Million Btu)
Jun 78	2.13	11.39	164.54	-3,961	164,540	151.0
Jul 78	2.37	11.49	188.89	-4,061	188,890	175.0
Aug 78	2.22	12.60	181.21	-4,342	181,210	166.4
Sep 78	1.80	11.11	143.57	-3,783	143,570	130.7
Total	8.52	46.59	678.21	-16,147	678,210	623.1
Average	2.13	11.65	169.55	-4,037	169,553	155.8

NOTE:

Negative amounts under electric savings indicate expenditures above the conventional operating costs of the system.

6. REFERENCES

1.* Monthly Performance Report, ARATEX, SOLAR/2008-78/06, Department of Energy, Washington (June, 1978).

2.* Monthly Performance Report, ARATEX, SOLAR/2008-78/07, Department of Energy, Washington (July, 1978).

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* Copies of these reports may be obtained from:
U. S. Department of Energy
Technical Information Center
P. O. Box 62
Oak Ridge, Tennessee 37830

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APPENDIX A

DEFINITIONS OF PERFORMANCE FACTORS

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 solar energy incident on the gross collector array. 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. The particular performance factors provided in this form are listed on Figure 4 and defined as follows:

- 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 solar energy incident on the gross collector array area. This is the area of the collector array energy-removing 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.

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

- ECSS SOLAR CONVERSION EFFICIENCY (CSCEF) is the ratio of the solar energy delivered to the load subsystems to the total energy incident on the collector array. In general, this will be a rather small number, since it includes effects of the overall collection efficiency, losses by the collectors, transport mechanism, storage device, and losses imposed by the control system.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow into 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.

- 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 subsytem, (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 FOSSIL FUEL (HWAF) is the amount of fossil fuel 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.

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

- 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.

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.

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

- <u>AMBIENT TEMPERATURE (TA)</u> is the average temperature of the environment at the site.

- <u>WIND DIRECTION (WDIR)</u> is the average direction of the prevailing wind.

- <u>WIND SPEED (WIND)</u> is the average wind speed measured at the site.

- <u>DAYTIME AMBIENT TEMPERATURE (TDA)</u> 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 FOR ARATEX SERVICES, INCORPORATED

I. INTRODUCTION

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

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

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

$$\text{Solar Energy Available} = (1/60)\ \Sigma\ [\text{I001} \times \text{Area}] \times \Delta\tau$$

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

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

$$\text{Collected Solar Energy} = \Sigma\ [\text{W100} \times \text{CP} \times \text{RHO} \times (\text{T150} - \text{T100})] \times \Delta\tau$$

Where W100 is the flow rate of the heat transfer fluid in gal/min, CP and RHO are the specific heat and density, and T100 and T150 are the temperatures of the fluid before and after passing through the heat exchanging component. Frequently this temperature difference is referred to as simply TD100. The product W100 x RHO is often combined and represented as M100.

For electrical power, a general example is

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

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

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

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - ALL UNITS ARE MILLION BTU UNLESS OTHERWISE SPECIFIED

- MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATICS FIGURE 3-1 AND 3-2

SITE SUMMARY REPORT

INCIDENT SOLAR ENERGY

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

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

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

COLLECTED SOLAR ENERGY

$= \sum [M100 \times CP \times (T150 - T100)] \times \Delta\tau$

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

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

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

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

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOADS/INCIDENT SOLAR ENERGY

ECSS OPERATING ENERGY

$= (56.88) \sum EP101 \times \Delta\tau$

WHENEVER COLLECTORS ARE OPERATING

TOTAL SYSTEM OPERATING ENERGY

= ECSS OPERATING ENERGY + HOT WATER OPERATING ENERGY

TOTAL ENERGY CONSUMED

= AUXILIARY FOSSIL ENERGY + SYSTEM OPERATING ENERGY + SOLAR ENERGY COLLECTED

HOT WATER LOAD

= HOT WATER AUXILIARY THERMAL ENERGY + HOT WATER SOLAR ENERGY

TOTAL SYSTEM LOAD

= HOT WATER LOAD

HOT WATER SOLAR FRACTION (PERCENT)

= 100 x HOT WATER SOLAR ENERGY/HOT WATER LOAD

HOT WATER SOLAR ENERGY

$$= \Sigma \; [M300 \times CP \times (T350 - T300)] \times \Delta\tau$$

TOTAL SOLAR ENERGY USED

= HOT WATER SOLAR ENERGY

HOT WATER OPERATING ENERGY

$$= 56.88 \; \Sigma \; [EP301 + EP302 + 0.6 \times EP304] \times \Delta\tau$$

TOTAL OPERATING ENERGY

= ECSS OPERATING ENERGY + HOT WATER OPERATING ENERGY

HOT WATER AUXILIARY THERMAL ENERGY

$$= \Sigma \; [M301 \times CP \times (T351 - T301)] \times \Delta\tau$$

TOTAL AUXILIARY THERMAL ENERGY

= HOT WATER AUXILIARY THERMAL ENERGY

HOT WATER AUXILIARY FOSSIL FUEL

= 1.67 x HOT WATER AUXILIARY THERMAL ENERGY

TOTAL AUXILIARY FOSSIL FUEL

= HOT WATER AUXILIARY THERMAL ENERGY

HOT WATER ELECTRICAL SAVINGS

= 1.67 x HOT WATER SOLAR ENERGY

TOTAL AUXILIARY ELECTRIC FUEL SAVINGS

= HOT WATER ELECTRIC FUEL SAVINGS

HOT WATER FOSSIL FUEL SAVINGS

= 1.67 x HOT WATER SOLAR ENERGY

TOTAL FOSSIL FUEL SAVINGS

= HOT WATER FOSSIL FUEL SAVINGS

SYSTEM PERFORMANCE FACTOR

= SYSTEM LOAD/(HOT WATER AUXILIARY FOSSIL + 3.33 x SYSTEM OPERATING ENERGY)

OPERATIONAL INCIDENT ENERGY

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

WHENEVER COLLECTOR PUMP IS RUNNING

COLLECTOR ARRAY EFFICIENCY

= SOLAR ENERGY COLLECTED/INCIDENT SOLAR ENERGY

ENERGY TO STORAGE

= Σ [M100 x CP x (T150 - T100)] x $\Delta\tau$

ENERGY FROM STORAGE

= Σ [M300 x CP x (T350 - T300)] x $\Delta\tau$

CHANGE IN STORED ENERGY

= STOCAP x (TSTM x RHO x CP - $TSTM_p$ x RHO_p x CP_p)

WHERE THE SUBSCRIPT p INDICATES VALUES OBTAINED FROM PREVIOUS SCANS

STORAGE AVERAGE TEMP (DEGREES F)

= $(1/60) \times \Sigma$ [(T200 + T201 + T202) / 3] x $\Delta\tau$

STORAGE EFFICIENCY

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

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOADS/INCIDENT SOLAR ENERGY

SUPPLY WATER TEMP (DEGREES F)

$= (1/60) \times \Sigma\ T300 \times \Delta\tau$

HOT WATER AVG. TEMP (DEGREES F)

$= (1/60) \times \Sigma\ T351 \times \Delta\tau$

HOT WATER USED (GALLONS)

$= \Sigma\ W302\ \Delta\tau$

DAYTIME AMBIENT TEMP (DEGREES F)

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

$\pm$ THREE HOURS FROM SOLAR NOON

WIND DIRECTION (DEGREES)

$= (1/60) \times \Sigma\ D001 \times \Delta\tau$

WIND SPEED (M.P.H.)

$= (1/60 \times \Sigma\ V001 \times \Delta\tau$

HEAT RECOVERY SYSTEM

$= \Sigma\ [M303 \times CP \times (T300 - T303)] \times \Delta\tau$