SOLAR/1015-79/14
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SOLAR-ENERGY-SYSTEM-PERFORMANCE EVALUATION

SOLAR/1015--79/14

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PERL-MACK ENTERPRISES, INC.
SINGLE-FAMILY RESIDENCE,
DENVER, COLORADO

APRIL 1978 THROUGH MARCH 1979

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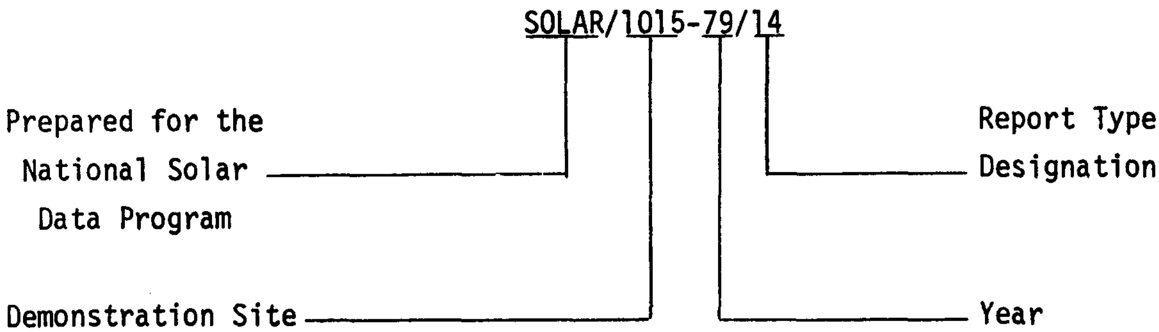
NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the Perl-Mack Enterprises, Inc., project site is designated as SOLAR/1015-79/14. 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.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth in order to achieve a substantial reduction in non-renewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

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

The International Business Machines Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the System Performance Evaluation Report, is published on a regular basis. Each parameter presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network.

All reports issued by the National Solar Data Program for the Perl-Mack Enterprises, Inc. solar energy system are listed in Section 6, References.

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Perl-Mack Enterprises, Inc. solar energy system. The analysis covers operation of the system from April 1978 through March 1979. The Perl-Mack Enterprises, Inc, solar energy system provides space heating and domestic hot water to a single-family dwelling in Denver, Colorado. A more detailed system description is contained in Section 3. Analysis of the system performance was accomplished using a system energy balance technique described in Section 4. Section 2 presents a summary of the results and conclusions obtained while Section 5 presents a detailed assessment of the system thermal performance.

Acknowledgement is extended to the home owner, Mr. Richard Nystrum, for his cooperation during the period of data gathering. Various on-site problems during the reporting period were better correlated with observed data, which helped in the differentiation between system and instrumentation anomalies.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report provides an operational summary of the Perl-Mack Enterprises, Inc., solar energy system installed in a single family dwelling in Denver, Colorado. This analysis is conducted by evaluation of measured system performance and by comparison of measured weather data with long-term average climatic conditions. The performance of major subsystems is also presented.

The measurement data were collected [Reference 7]* by the National Solar Data Network (NSDN) [1] for the period April 1978 through March 1979. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report.

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

Monthly values of average daily insolation and average outdoor ambient temperature measured at the Perl-Mack Enterprises, Inc., site are presented in Table 5.1-1. Also presented in the table are the long-term, average monthly values for these climatic parameters. Weather conditions were severe in December and January, but served to show the extremes of solar subsystem behavior and the dramatic contrast in solar energy losses observed between winter and summer system operation.

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*Numbers in brackets designate References found in Section 6.

For the purposes of this Solar Energy System Performance Evaluation, monthly performance reports were regenerated reflecting a change in the characteristics of the collector working solution, consideration of the heat capacity of concrete in the thermal storage tank and the use of actual natural gas billings to the homeowner as the basis for auxiliary energy computation. These modifications significantly change the numerical values of selected performance factors, but have not changed the trends and basic findings reported in individual monthly performance reports.

The Perk-Mack Enterprises, Inc., solar system operated continuously for the twelve months, April 1978 through March 1979. The only system malfunction was a defective valve in the solar heating subsystem. This resulted in reduced flow in the storage-to-furnace liquid lines. This occurred when the solar heating subsystem was reactivated in the fall.

Instrumentation was reworked when it was discovered that the temperature probes in the energy collection and storage subsystem were being saturated by working fluid temperatures in excess of 160°F. The month of June was partially affected. Estimates of excesses in temperatures were made, and an energy balance was achieved for the month. Data transmission problems were encountered sporadically, but the data was averaged (bridging technique) over the data gaps.

The most significant problem noted, based on a physical inspection of the site and the measured performance data, is the complete lack of insulation on copper tubing throughout the solar and auxiliary subsystems. As a result, uncontrolled solar energy losses were large and dominated the system performance. The major loss contribution was from the storage tank, associated plumbing and heat exchangers.

Energy savings were $45 for the twelve month period. These results are based on the normal performance factors used to compare solar installations, wherein only the measured (controlled) solar energy distribution to the load subsystems is considered.

Given that the solar energy losses within the controlled space aid space heating and detract from cooling, estimates have been made of the effects of the losses. Crediting losses to heating and subtracting the penalty to cooling during the summer months, the net savings for the twelve month period were $75.

Because the design intent is not fully understood relative to the trade-off in the decision not to insulate plumbing, and because loss effects are estimated, it is observed that the average savings lay between $3.78/ month and $6.25/month.

A total of 79.89 million Btu of solar energy were collected during the reporting period, and of this total, 66.74 million Btu were delivered to the storage tank. A total of 25.65 million Btu was removed from storage for support of subsystem loads and 20.41 million Btu were actually delivered to the space heating and the domestic hot water loads. Of the 79.89 million Btu of solar energy collected, 57.08 million Btu were lost into the conditioned living space.

The collected solar energy of 79.89 million Btu represents 31 percent of the total solar energy incident on the collector array and 45 percent of the incident solar energy during the time that collection was actively taking place.

The storage subsystem contributed the major portion of the energy loss to the controlled space. The effective storage loss coefficient ranged from 33.8 to 153.7 in January and in May, respectively. This variation is due to the relative contribution of loss from the storage tank proper and from the associated plumbing at different times of the year (function of storage tank temperature).

The domestic hot water subsystem benefitted from solar energy more than the space heating subsystem because the city water is heated by the storage tank during consumption. The hot water load was 20.66 million Btu and solar energy contributed 11.30 million Btu.

The space heating subsystem load during the reporting period was 27.46 million Btu, and solar energy supplied 9.11 million Btu of this load. This represents a heating solar fraction of 33 percent. Due to very poor mid-winter insolation, storage tank temperatures were low enough to occasionally prevent any solar contribution to space heating because of controller settings. One malfunction, a restriction of flow, caused excessive pump operation during the month of November. The problem was corrected by the home owner.

The Perl-Mack Enterprises, Inc., solar installation experienced abnormal seasonal weather conditions. June and July were warmer than the long-term average. December and January were very cold and broke long standing records. Insolation was 22 percent lower than the long-term average. The localized difference between the site location and the Denver airport are not likely the reason. No absolute reference is obtainable for comparable long-term insolation. However, substantially reduced insolation was observed from November 1978 through March 1979. Performance of the solar system was accordingly penalized since the solar energy availability was reduced.

In conclusion, a recommendation is made that the Perl-Mack Enterprises, Inc., solar system be modified to insulate all plumbing and heat exchangers carrying solar working fluids. The objective, aside from improved creature comfort with a controlled demand for energy, is to make performance comparisons with the modified configuration.

3. SYSTEM DESCRIPTION

The Perl-Mack Enterprises, Inc. site is a single-family dwelling, 2,229 square feet of living area, in Denver, Colorado. The solar energy system is designed to provide approximately 68 percent of the annual space heating and hot water energy requirements for the home. It has an array of flat-plate collectors, manufactured by Miromit, with a gross area of 470 square feet that faces south at an angle of 30 degrees to the horizontal. A water-propylene glycol solution is used as the medium for delivering solar energy from the collector array to water thermal storage located in the basement. The energy is stored in a concrete tank with a 853 gallon water capacity after the transfer fluid passes through a liquid-to-liquid heat exchanger. Preheating of incoming city water is accomplished in a 40-gallon tank immersed within the 853-gallon tank. A gas burner in a conventional, 40-gallon hot-water tank furnishes auxiliary energy for water heating. When solar energy is insufficient, a forced-air, natural-gas furnace provides additional energy for space heating.

The system, shown schematically in Figure 3-1, has five modes of solar operation.

Mode 1 - Collector-to-Storage: This mode is entered when the collector outlet temperature exceeds the water thermal storage temperature by 10°F (adjustable). The transfer fluid is circulated through the collectors, through the heat exchanger HX2, and back to the collectors until the temperature differential drops to less than 2°F.

Mode 2 - Storage-to-Space Heating: This mode prevails when the room temperature drops to the setting of the thermostat, and the temperature in the water thermal storage is 90°F or higher. Energy from storage is transferred to liquid-to-air heat exchanger HX1 located in the air-handling unit.

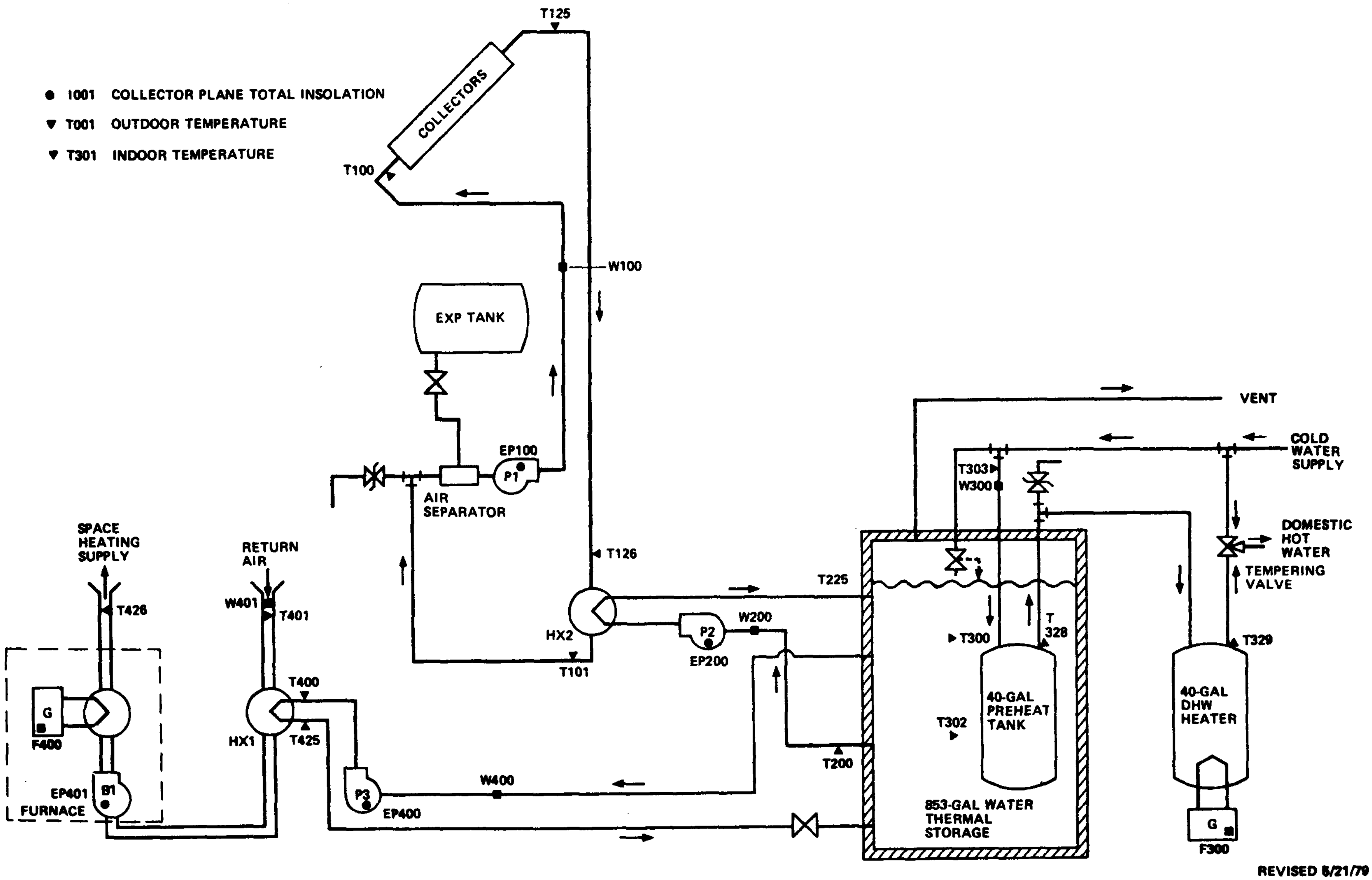

FIGURE 3-1 PERL-MACK ENTERPRISES SOLAR ENERGY SYSTEM SCHEMATIC

Mode 3 - Domestic Water Preheat: This mode exists when there is a demand for hot water. Incoming city water flows through the preheat tank immersed in the water thermal storage and then to the conventional hot water heater (DHW heater).

Mode 4 - Excess Heat Rejection: This mode occurs when the water thermal storage temperature exceeds 170°F and mode 1 has been terminated. In this mode, energy from storage is transferred to the collectors for exchange of energy to the outside ambient air. In addition, vapor in the water thermal storage is vented to the outside of the house.

Mode 5 - Snow Removal from Collector: This mode is accomplished by a manual override switch which permits the homeowner to turn on the collector and storage pumps to transfer energy from water thermal storage to the collectors. The purpose of this mode is to remove snow from the collectors before normal insolation and collection would be expected to begin. This mode terminates automatically after a preset time interval of approximately 15 minutes.

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Perl-Mack Enterprises, Inc. solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each component subsystem.

Each month a summary of overall performance of the Perl-Mack Enterprises, Inc., site and a detailed subsystem analysis are published. Monthly reports for the period covered by this System Performance Evaluation, April 1978 through March 1979, are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

5. PERFORMANCE ASSESSMENT

The performance of the Perl-Mack Enterprises, Inc. solar energy system has been evaluated for the April 1978 through March 1979 time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load and the measured values for solar energy used and system solar fraction are presented. Also presented, where applicable, are the expected values for solar energy used and system solar fraction. The expected values have been derived from a modified f-chart* analysis which uses measured weather and subsystem loads as inputs. The model used in the analysis is based on manufacturers' data and other known system parameters. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level has been presented. The second view presents a more in-depth look at the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the space heating subsystem. Included in this area are all parameters pertinent to the operation of each individual subsystem.

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

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* f-chart is the designation of a procedure for designing solar heating systems. It was developed by the Solar Energy Laboratory, University of Wisconsin-Madison.

5.1. Weather Conditions

Monthly values of the total solar energy incident in the plane of the collector array and the average outdoor temperature measured at the Perl-Mack Enterprises, Inc. site during the report period are presented in Table 5.1-1.

Also presented in Table 5.1-1 are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from Reference Monthly Environmental Data for Systems in the National Solar Data Network [4]. A complete yearly listing of these values for the site is given in Appendix C.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are accumulated. Likewise, if a day's average temperature was 80°F, then 15 cooling degree days are accumulated. The total number of heating and cooling degree-days are summed monthly.

For the period April 1978 through March 1979, the measured daily average incident solar energy per unit area was 19 percent lower than the long-term average daily insolation. This comparison can be misleading, because of the great variation in the weather during the winter months of December and January. The variation in long-term and measured values was 47 percent in December and January, 11 percent for the April through October, and 33 percent for the period November through March. It may be concluded that long-term average data is too high for design purposes, and may be significantly in error on individual months.

Ambient temperature averages for the period compare favorably. In December, the temperature was 33 percent lower than the long-term average, and 37 percent lower in January. The heating degree-days show good comparison but large variation in the very cold months of January and February. Cooling degree-days were measured to be 140 percent greater in July than the long-term average, and 30 percent lower in August.

TABLE 5.1-1

WEATHER CONDITIONS

	Daily Incident Solar Energy Per Unit Area (30° Tilt)(Btu/Ft^2-Day)		Ambient Temperature (°F)		Heating Degree Days		Cooling Degree-Days	
Month	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average
Apr 78	1,776	1,996	49	48	478	525	0	0
May 78	1,665	2,035	53	57	388	253	21	0
Jun 78	1,802	2,138	67	66	96	80	144	110
Jul 78	1,887	2,109	75	73	0	0	599	248
Aug 78	1,881	2,071	70	72	22	0	147	208
Sep 78	1,956	2,022	66	63	117	120	30	54
Oct 78	1,671	1,830	52	52	419	408	2	5
Nov 78	1,002	1,460	37	39	851	768	0	0
Dec 78	716	1,329	22	33	1,279	1,004	0	0
Jan 79	758	1,462	19	30	1,429	1,088	0	0
Feb 79	1,259	1,664	33	33	904	902	0	0
Mar 79	1,482	1,908	40	37	771	868	0	0
Total	--	--	--	--	6,754	6,016	943	625
Average	1,488	1,835	49	50	563	501	79	52

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and 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 energy is defined to be 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 system thermal performance is summarized in Tables 5.2-1 and 5.2-2. The solar energy collected was 79.89 million Btu for the 12-month period, with abnormally low collection in December and January. The system load of 48.12 million Btu is the sum of the solar energy and the auxiliary fossil energy supplied to the space heating and domestic hot water subsystems. The system solar fraction was 58 percent, and is the ratio of the solar energy supplied to the loads and the system load. Note that this is a monthly weighted average based on the relative load of the contributing load subsystems.

The solar energy system COP (defined as the total solar energy delivered to the load divided by the total solar energy system operating energy) averaged 7.23 for the 12-month period. The collector array subsystem COP and the space heating subsystem solar COP for the period were 23.64 and 52.04, respectively. These values again relate the amount of solar energy associated with a particular subsystem to the amount of electrical energy required to operate the solar portion of that subsystem. As such, the COP serves as an indicator of how well the system operated.

TABLE 5.2-1

SYSTEM THERMAL PERFORMANCE

Month	Solar Energy Collected (Million Btu)	System Load (Million Btu)	Solar Energy Used (Million Btu)		Solar Fraction (Percent)	
			Expected	Measured	Expected	Measured
Apr 78	7.13	2.30	2.9	1.62	100	71
May 78	7.44	2.38	2.5	1.35	100	57
Jun 78	8.89	1.09	1.3	0.72	100	65
Jul 78	8.86	1.22	1.6	1.05	100	86
Aug 78	8.83	1.36	1.7	1.22	100	90
Sep 78	8.59	1.57	1.7	1.52	100	97
Oct 78	7.08	2.32	2.9	1.52	100	66
Nov 78	4.50	4.98	3.7	1.49	68	26
Dec 78	2.93	9.02	2.7	1.74	28	19
Jan 79	3.20	9.88	3.0	2.25	29	21
Feb 79	5.76	6.01	4.9	2.98	75	51
Mar 79	6.68	5.99	5.9	2.95	87	48
Total	79.89	48.12	34.9	20.41	--	--
Average	6.66	4.01	2.9	1.70	65	58

TABLE 5.2-2

SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

Month	Solar Energy System COP	Collector Array Subsystem COP	Space Heating Subsystem Solar COP
Apr 78	5.19	26.02	89.02
May 78	4.28	27.76	72.00
Jun 78	5.40	21.74	-
Jul 78	4.80	23.63	-
Aug 78	5.40	25.08	-
Sep 78	5.66	22.72	-
Oct 78	6.38	23.29	73.33
Nov 78	6.76	21.84	22.28
Dec 78	11.16	19.66	50.87
Jan 79	12.98	20.9	51.07
Feb 79	11.45	23.41	58.60
Mar 79	11.05	25.21	67.67
Total Period	7.23	23.64	52.04

5.3 Subsystem Performance

The Perl-Mack Enterprises, Inc. solar energy installation may be divided into four subsystems:

1) Collector array
2) Storage
3) Domestic Hot Water
4) Space Heating.

Each subsystem is evaluated by the techniques defined in Section 4 and is numerically analyzed each month for the monthly performance reports. This section presents the results of integrating the monthly data available on the four subsystems for the period April 1978 through March 1979.

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

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

where: η_c = Collector Array Efficiency (CAREF)

Q_s = Collected Solar Energy (SECA)

Q_i = Incident Solar Energy (SEA).

The gross collector array area is 469.7 square feet. The 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 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:

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

where: Q_s = Collected Solar Energy (SECA)

Q_{oi} = Operational Incident Energy (SEOP)

Q_p = Gross Collector Area (product of the number of collectors and the total envelope area 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).

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

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
Apr 78	25.03	7.13	0.28	16.30	0.44
May 78	24.11	7.44	0.31	15.58	0.48
Jun 78	25.40	8.89	0.32	18.98	0.36
Jul 78	27.48	8.86	0.32	19.59	0.46
Aug 78	27.39	8.83	0.32	19.16	0.47
Sep 78	27.57	8.59	0.31	20.14	0.43
Oct 78	24.33	7.08	0.29	16.95	0.42
Nov 78	14.2	4.50	0.32	10.15	0.45
Dec 78	10.42	2.93	0.28	6.77	0.44
Jan 79	11.14	3.20	0.29	7.15	0.45
Feb 79	16.56	5.76	0.35	12.68	0.46
Mar 79	21.59	6.68	0.32	15.79	0.43
Total	255.14	79.89	---	179.24	---
Average	21.26	6.66	0.31	14.94	0.45

This latter efficiency term is not the same as collector efficiency as represented by the ASHRAE Standard 93-77 [5]. 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 operational collector 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.

Collector array efficiency may be viewed from two perspectives. The first assumes that the efficiency be based upon all available solar energy; however, that point of view makes the operation of the control system a part of array efficiency. For example, energy may be available at the collector, but the collector fluid temperature is below the control minimum, thus the energy is not collected. The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Table 5.3.1-1.

The second viewpoint assumes the efficiency be based upon only the incident energy during periods of collection. The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency." Efficiency computed by this method is used in the following discussion.

It was noted in the system description that in Mode 1, Collector-to-Storage, the collection pumps are started when the collector outlet temperature exceeds the water thermal storage temperature by 10°F, and that collection is stopped at a 2°F differential. The home owner has not controlled these settings, nor has there been any seasonal adjustment made by service personnel. John C. Ward [Reference 8], Professor of Civil Engineering, Colorado State University, has suggested that these settings should be 20°F and 10°F, respectively, so that the rate of energy delivery exceeds the rate of electrical energy consumption. This result is implicit in the collector array COP of Table 5.2-2, but no experiments were made to improve the COP.

Excess Heat Rejection (Mode 4) is an operation of the collector subsystem to remove energy from the thermal storage when storage temperatures exceed 170°F. This can occur only after the collector pumps would have otherwise been shut off by the controller because the insolation was too low to provide energy. This collection and then rejection of energy would not be required if provision had been made for stopping collection during periods of high insolation. During the months of June through September, 35.17 million Btu were collected, and 2.71 million Btu were extracted from storage for rejection by the collectors. This represents 7.7 percent of the collected energy, and this energy was collected and then rejected at an expense of 0.23 million Btu of operating expense (86 kwh).

Snow removal (Mode 5) was not exercised.

Monthly performance reports issued prior to December 1978 reflected performance based on an assumed collector working solution of 50 percent ethylene glycol and water. Subsequent chemical analysis of the solution showed the actual solution to be 35 percent propylene glycol and water. It has been reasonably established that no change in the solution (including no make up water) has been made since the original installation. The change in specific heat and in density has been reflected in the data presented in this report, and therefore, results will show variation from monthly performance reports. The trends and conclusions are unchanged.

The physical installation of the 20 collector panels is on the south facing roof of the uninsulated garage. The collection manifolding is connected to copper tubing which is uninsulated. Temperature probes measuring the inlet and exit working fluid temperatures are in the uninsulated tubing at the location where the tubing enters the wall vertically between the garage and the house. All losses from the measurement point to thermal storage are considered losses which contribute to the house heating or cooling load. Losses between the point of measurement and the collector array are unaccounted for, and are presumed to be contributing to collector array performance (as are manifolds).

The Perl-Mack Enterprises, Inc. solar energy system has 20 panels (Miromit, Collector Model 205) with 10 parallel flow paths to the fluid collection manifolds. The physical array has 2 horizontal rows and 10 vertical columns of continuous panels. Table 5.3.1-2 presents a comparison of the actual performance of the collector array, for the month of March 1979, to the performance prediction based on linear instantaneous efficiency data provided by the manufacturer for a single panel. Linear and second order regression techniques were used in curve fitting and the coefficients A0, A1, A2, and R**2 were derived both for the month and for the data accumulated during the preceding months of the reporting period (long-term). Actual data represents the amount of solar energy collected by the array in March. The error is the deviation of the actual field performance for the array from the laboratory panel data, on a daily basis, from the regression curve for March. This may be expressed as the ratio of the difference between the actual and predicted data to the predicted data. Note that the actual array collection for the month of March 1979 is slightly different than the collected solar energy for the same month given in Table 5.3.1-1. Both summaries are derived from identical data records; however, the treatment of short periods of "dropped" data is different. The difference is not significant. The average error between the laboratory panel under the same conditions experienced by the array and the array performance is given for the month of March 1979 as -12 percent. For the entire reporting period from April 1978 through March 1979, the same derived error is -1.7 percent, which is the more meaningful number. This means that the manufacturer has predicted 1.7 percent greater collection than was actually observed. Should the uninsulated copper pipes between the collector instrumentation and the array proper be insulated, it could be projected that the measurable collected energy would be greater under identical collector operating points. Accordingly, the manufacturer's projection would tend toward a smaller collection differential, with respect to the array performance.

TABLE 5.3.1-2

ENERGY GAIN COMPARISON
MARCH

SITE: PERL - MACK DENVER, CO

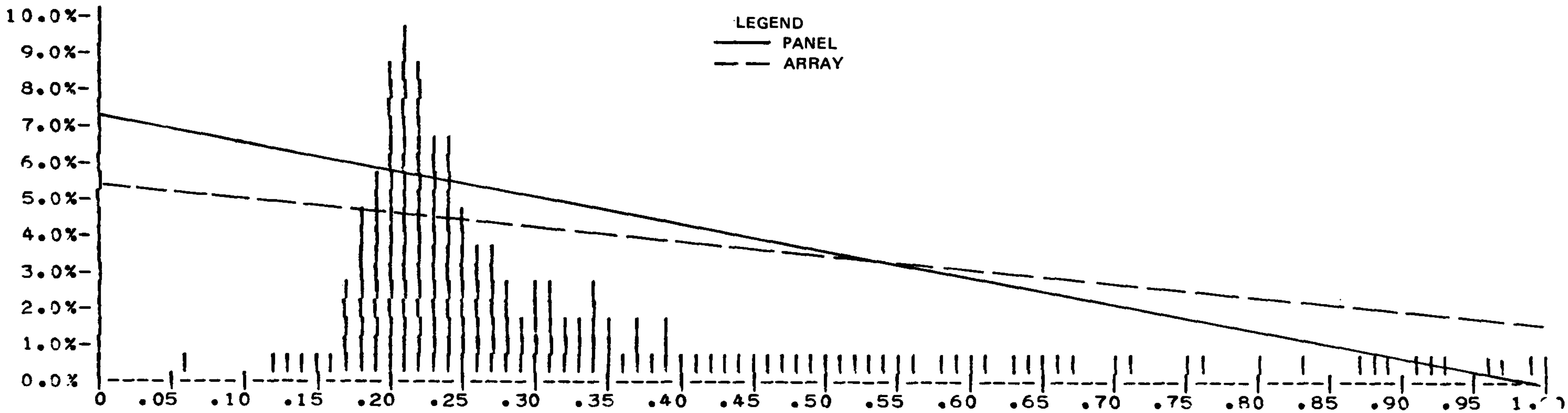
DAY	ACTUAL	ERROR			
		FIELD DERIVED			LAB
		MONTH	LONG TERM	2ND ORDER	PANEL
1	2.688E+05	0.085	0.062	0.119	-0.079
2	0.000E+00	0.000	0.000	0.000	0.000
3	1.767E+05	0.008	-0.019	0.028	-0.156
4	3.902E+05	0.129	0.109	0.174	-0.033
5	3.660E+05	0.073	0.045	0.064	-0.105
6	2.149E+05	0.021	0.002	0.016	-0.128
7	3.825E+05	0.091	0.060	0.068	-0.098
8	0.000E+00	0.000	0.000	0.000	0.000
9	2.371E+05	-0.003	-0.029	0.016	-0.166
10	3.930E+05	0.102	0.077	0.157	-0.070
11	3.959E+05	0.025	-0.009	0.003	-0.165
12	3.739E+05	0.029	-0.000	0.002	-0.151
13	1.516E+05	0.405	0.422	0.493	0.320
14	3.786E+05	0.017	-0.014	-0.007	-0.166
15	3.911E+05	0.106	0.083	0.084	-0.067
16	2.664E+05	0.105	0.074	0.080	-0.086
17	2.322E+05	0.020	-0.007	0.000	-0.153
18	1.936E+04	0.234	0.223	0.215	0.092
19	7.495E+04	0.027	-0.002	0.092	-0.145
20	0.000E+00	0.000	0.000	0.000	0.000
21	0.000E+00	0.000	0.000	0.000	0.000
22	0.000E+00	0.000	0.000	0.000	0.000
23	2.561E+05	-0.135	-0.166	-0.113	-0.295
24	4.142E+05	0.032	0.002	0.012	-0.148
25	3.577E+05	-0.005	-0.033	-0.030	-0.178
26	4.086E+04	0.170	0.197	0.301	0.142
27	3.984E+05	0.101	0.062	0.075	-0.107
28	2.567E+05	0.096	0.066	0.088	-0.093
29	2.137E+05	0.147	0.125	0.142	-0.026
30	3.205E+05	-0.011	-0.036	-0.029	-0.174
31	0.000E+00	0.000	0.000	0.000	0.000
	6.970E+06	0.055	0.028	0.052	-0.120

CURVE	COEFFICIENTS			
	A0 (FRTA)	A1 (FRUL)	A2 (*)	R**2
PANEL	0.730	-0.730	N.A.	N.A.
MONTH	0.484	-0.218	N.A.	0.085
LT1ST	0.526	-0.344	N.A.	0.234
LT2ND	0.447	0.245	-1.045	N.A.

Figure 5.3.1-1 presents a histogram, for the month of March 1979, with the percentage of time that collection took place within an operating point interval. Sixty percent of the collection is centered at an operating point of 0.21. Superimposed on the histogram is a plot of the annual average performance for the panel and array. The array efficiency is 45 percent, and the manufacturer's panel data indicates a corresponding efficiency of 60 percent. Note that the ordinate should be interpreted as 100 percent full scale for collector efficiency.

PERL - MACK DENVER, CO

COLLECTOR TYPE: MIRO-MIT COLLECTOR MODEL: 205



OPERATING POINT HISTOGRAM - MARCH

FLUID PROPERTIES - MARCH

PROPYLENE GLYCOL/WATER 35% BY VOLUME				
	COEFFICIENTS			
PROPERTY	A0	A1	A2	A3
SPECIFIC HEAT	9.028E-01	9.218E-05	8.672E-07	
DENSITY	8.712E+00	-1.517E-03	-6.030E-06	

ARRAY FLOW RATE 14.81 GPM

PANEL FLOW RATE 1.48 GPM

AVERAGE TEMPERATURE GAIN 7.96 DEGR FAHRENHEIT

LONG TERM CURVE FIT VALID FROM 0.131 TO 0.394 .

FIGURE 5.3.1-1 COLLECTOR ARRAY OPERATING POINT HISTOGRAM AND INSTANTANEOUS EFFICIENCY CURVES

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, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \qquad (3)$$

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) (STECH).

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

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

Note: Rejected energy, RJESTEO, is included in the term Q_{so} when mode 4 is operative.

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

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

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

$$C = (Q_{si} - Q_{so} - \Delta Q_S)/[(\overline{T}_s - \overline{T}_a) \times t] \; \frac{\text{Btu}}{\text{Hr-°F}} \qquad (4)$$

where:

C = effective storage heat transfer coefficient

Q_{si} = energy to storage (STEI)

Q_{so} = energy from storage (STEO)

ΔQ_s = change in stored energy (STECH)

$\overline{T}s$ = storage average temperature (TS)

$\overline{T}_a$ = average ambient temperature in the vicinity of storage (TE)

t = number of hours in the month (HM).

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [6]. It has been calculated for each month in this report period and included, along with Storage Average Temperature, in Tables 5.3.2-1 and 5.3.2-2.

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)	Effective Storage Heat Loss Coefficient (Btu/Hr°-F)
Apr 78	6.07	1.77	-0.17	0.26	123	124.0
May 78	6.73	1.46	0.13	0.24	121	153.7
Jun 78	6.89	2.25*	0.18	0.35	136	108.4
Jul 78	6.79	1.80*	0.04	0.27	149	100.7
Aug 78	6.76	1.90*	- 0.09	0.27	148	102.2
Sep 78	6.90	2.14*	0.05	0.32	147	102.2
Oct 78	6.07	1.94	-0.14	0.30	130	112.6
Nov 78	3.92	1.63	-0.22	0.36	105	109.3
Dec 78	2.61	1.92	-0.15	0.68	87	66.5
Jan 79	2.79	2.35	0.01	0.85	87	33.8
Feb 79	5.14	3.23	0.11	0.65	97	103.0
Mar 79	6.04	3.26	-0.09	0.53	105	120.5
Total	66.74	25.65	-0.34	--	--	--
Average	5.56	2.14	-0.03	0.38	120	103.1

*Includes Mode 4 rejected energy.

TABLE 5.3.2-2

EFFECTIVE STORAGE HEAT LOSS COEFFICIENT

Month	Thermal Storage Losses (Btu/mo.)	T_s (°F)	T_a (°F)	Coefficient C Btu/Hr-°F
Apr 78	4.47	123	73	124
May 78	5.15	121	76	154
Jun 78	4.45	136	79	108
Jul 78	4.95	149	83	100
Aug 78	4.94	148	83	102
Sep 78	4.71	147	83	102
Oct 78	4.27	130	79	112
Nov 78	2.52	105	73	109
Dec 78	0.84	87	70	67
Jan 79	0.43	87	70	34
Feb 79	1.80	97	71	103
Mar 79	2.87	105	73	121

The thermal storage tank is a square concrete septic tank, modified for solar use, with internal painted surfaces, insulation on the sides (no insulation at the bottom) and an insulated cover. The outside dimensions are 7x7x4 feet. The volume of water is 114 ft^3 and the volume of the concrete is 64 ft^3. Since water and concrete have different specific heat and mass, the enthalpy changes with time will be out of phase. It is assumed that over the period of a month, phase differences will not be of consequence since they are diurnal in nature. Separate enthalpy changes are integrated at the nominal 5.33 minute sampling interval.

The thermal storage tank is the house basement and losses have been excessive as may be seen from the effective storage Heat Loss Coefficient presented in Table 5.3.2-1. Based on monthly performance reporting, steps have been taken to rectify this situation. Reference to Figure 3-1, the system schematic, will show that the boundary of the storage subsystem instrumentation is the input to the tank and the input to the liquid to air heat exchanger in the furnace. To further assess the losses, the storage subsystem is defined as a storage tank and associated plumbing. Losses of energy from the storage subsystem plumbing include:

- Heat losses from inlet pipes, including heat exchanger HX2. Because there are no check valves, these pipes carry water at nearly the storage tank temperature. Heat exchanger HX2 and pipes are not insulated. This energy loss is attributable to storage when there is no collection taking place.

- Heat losses from the outlet pipe from the 40-gallon preheat tank which is immersed in the storage tank (when there is no DHW demand).

- Heat losses from the outlet pipes, including heat exchanger HX1, none of which are insulated nor have check valves.

Losses from the storage tank proper are from water vapor losses to the vent, venting from under the unsealed top cover, and through the insulated sides and the uninsulated tank bottom to earth.

Referring to equation (4), let

$$C = C_1 + C_2 \qquad (5)$$

where:

C = effective storage subsystem heat transfer coefficient

C_1 = effective storage heat transfer coefficient for the storage plumbing

C_2 = effective storage heat transfer coefficient for the storage tank.

Equation 4 may also be written

$$C = \text{losses}/[\bar{T}_{si} - \bar{T}_a) \times t] \qquad (6)$$

where:

$\bar{T}_{si}$ = average temperature of the working fluid (water).

It can be assumed that all copper tubing associated with the storage subsystem (uninsulated) will maintain a temperature $\bar{T}_{si}$ which is presumed to be close to the average storage tank temperature $\bar{T}_s$. During December and January, these temperatures approach a temperature difference of approximately 17 degrees based on a house basement ambient temperature of 82°F. One would expect C_1 to be at a minimum and therefore C_2 would control the value of C during the winter months. The converse is true in the summer time when $(\overline{T}_{si} - \overline{T}_a)$ averaged 65°F. C_1 is the dominant factor in this seasonal period. Reference to Table 5.3.2-2 shows this effect quite dramatically. It may be concluded:

- The storage tank effective storage heat loss coefficient is approximately 50 Btu/Hr-°F.

- To correct the storage subsystem loss problem, the uninsulated plumbing should be given priority.

Of the 20.41 million Btu of solar energy used by the subsystem loads, 9.11 million Btu were supplied to the space heating subsystem and 11.30 million Btu were supplied to the domestic hot water subsystem. Reference to Figure 3-1, the system schematic shows that the domestic hot water system can utilize solar energy from the thermal storage tank at any time, since the average tank temperature is never lower than 85°F and the city water inlet temperature never higher than 65°F.

On the other hand, solar energy transfer from storage to space heating is inhibited below a sensed storage temperature of 90°F. During the extremely cold months of December and January (near coldest on record), with very poor insolation, the storage temperatures fell below the availability cutoff temperature of 90°F. It should be noted that, if in the long term these conditions were to prevail, the design of a like system should consider a smaller storage tank to provide elevated average temperatures. A constraint would be over-temperature conditions in the storage tank during the summer when domestic hot water is the only load.

5.3.3 Domestic Hot Water Subsystem

The performance of the Domestic Hot Water (DHW) subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total DHW 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 DHW solar fraction. The calculated DHW solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total DHW load supported by solar energy.

Operation of the DHW subsystem was nominal. Adjustments in the temperature of the hot water at the output of the hot water tank were made periodically by the home owner. Table 5.3.3-1 presents the overall performance of the Perl-Mack Enterprises, Inc. DHW subsystem for the period April 1978 through March 1979. The total DHW load for this period was 20.66 millon Btu. Note that the sum of the solar energy consumed and the auxiliary (gas) thermal energy is 23.94 million Btu. The difference of 3.28 million Btu represents the loss of energy from the hot water tank and plumbing between the points of measurement. The average solar fraction for the year was 55 percent, however, it should be noted that the monthly values correlate to the storage tank temperatures shown in Table 5.3.2-1. The monthly consumption is quite constant.

TABLE 5.3.3-1

DOMESTIC HOT WATER SUBSYSTEM PERFORMANCE

Month	Domestic Hot Water Heating Load (Million Btu)	Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Apr 78	1.47	0.89	.98	1.63	61
May 78	1.60	0.99	.63	1.06	62
Jun 78	1.01	0.68	.44	.73	67
Jul 78	1.22	1.05	.28	.47	86
Aug 78	1.36	1.22	.17	.28	90
Sep 78	1.55	1.50	.04	.07	97
Oct 78	1.83	1.08	.93	1.55	59
Nov 78	1.74	0.72	1.36	2.67	41
Dec 78	2.12	0.57	2.11	3.52	27
Jan 79	2.34	0.82	2.16	3.60	35
Feb 79	2.12	0.87	1.67	2.78	41
Mar 79	2.30	0.92	1.87	3.12	40
Total	20.66	11.30	12.64	21.48	--
Average	1.72	0.94	1.05	1.79	55

5.3.4 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 instrumentation used to measure the natural gas usage in both the space heating subsystem and the domestic hot water subsystem, covered in the preceding section, is a switch closure indicator. Monthly reports issued prior to December 1978 reflected the auxiliary energy measured with this device. Results correlated very poorly with the actual gas billing received by the home owner. Careful evaluation of the switch performance showed that it was a reliable indicator of the time and duration of the gas usage. It was therefore determined that the most accurate evaluation of heating, domestic hot water, and storage subsystem performance could be obtained by the following technique. The timing was retained and the magnitude of the usage in Btu/minute was determined such that the actual gas billing would be identically equal to the monthly fossil fuel consumption less the unmeasured pilot light usage. Pilot lights were estimated to use 400 cubic feet per month. At the altitude of Denver, the heating value of natural gas was assumed to be 840 Btu per cubic foot.

Since data was on file for the months of April 1978 through March 1979, all monthly reports for this period were recomputed. Accordingly, the data in this report will differ from the already published monthly performance reports prior to December 1978. It should be appreciated that a change in one subsystem will change many of the performance factors in other subsystems because of the load sharing interrelationship.

The performance of the Perl-Mack Enterprises, Inc. space heating subsystem is presented in Table 5.3.4-1. For the 12-month period from April 1978 to March 1979, the solar energy system supplied a total of 9.11 million Btu to the space heating load. The total heating load for this period was 27.46 million Btu, and the average solar fraction was 33 percent.

Operation was normal except for the month of November when an obstruction reduced the flow rate of water from the storage tank to the furnace heat exchanger from 10 to 3 gallons per minute. The home owner arranged for removal of one of two summer-winter shutoff valves in the line, and this cleared the problem. In general, the relatively low solar fractions during the December to February time period were due to poor insolation and low thermal storage temperatures.

TABLE 5.3.4-1

HEATING SUBSYSTEM PERFORMANCE

Month	Space Heating Load (Million Btu)	Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Apr 78	0.83	0.73	0.10	0.15	88
May 78	0.78	0.36	0.42	0.65	47
Jun 78	0.08	0.043	0.04	0.06	51
Jul 78	0.00	0.00	0.00	0.00	0
Aug 78	0.00	0.00	0.00	0.00	0
Sep 78	0.02	0.02	0.00	0.00	96
Oct 78	0.49	0.44	0.05	0.08	90
Nov 78	3.24	0.78	2.46	3.85	24
Dec 78	6.90	1.17	5.72	8.9	17
Jan 79	7.54	1.43	6.10	9.54	19
Feb 79	3.89	2.11	1.78	2.78	54
Mar 79	3.69	2.03	1.66	2.58	55
Total	27.46	9.11	18.33	28.59	--
Average	2.29	0.76	1.53	2.38	33

5.4 Operating Energy

Operating energy for the Perl-Mack Enterprises, Inc. 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 and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Total system operating energy includes electrical energy required to operate the blower in the furnace air-handling unit. This is shown as EP401 in Figure 3.1. Measured monthly values for subsystem operating energy are presented in Table 5.4-1.

No basis for comparison exists for evaluating the measured quantities with design criteria. However, these data apply in Table 5.2-2 in the derivation of the COP for each of the appropriate subsystems.

TABLE 5.4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Apr 78	0.27	0.07	0.34
May 78	0.27	0.07	0.34
Jun 78	0.41	0.01	0.42
Jul 78	0.38	0	0.38
Aug 78	0.35	0	0.35
Sep 78	0.38	0	0.38
Oct 78	0.30	0.05	0.35
Nov 78	0.21	0.38	0.59
Dec 78	0.15	0.28	0.43
Jan 79	0.15	0.33	0.48
Feb 79	0.25	0.34	0.59
Mar 79	0.27	0.28	0.55
Total	3.39	1.81	5.20
Average	0.28	0.15	0.43

5.5 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. For the heating subsystem, 0.64 is used, and for the domestic hot water subsystem, 0.60.

Table 5.6.1 shows the energy savings as derived from measured parameters, and may be referred to as the savings based on the controlled energy flow in the system. Since it deals with solar energy used by the loads and not with solar energy supplied to the loads, losses are assumed to be negligible. This table has been prepared to be consistent with the reporting of other solar installations.

In the Denver area, the ratio at the power plant for fossil fuel to electrical energy conversion is 0.25. This has been used to convert the electrical operating energy consumed by the solar system (shown as a negative savings) to fossil energy. The fossil energy equivalent at the source is the conversion of solar and electrical savings to a net savings. The fossil savings for the 12-month period are 17.33 million Btu. Based on an average of 0.0022 dollars/cubic foot, the annual savings was $45.35. This prorates to $3.78 per month.

If the assumption is made that the three sources of solar energy loss and one source of auxiliary loss are within the conditioned space then data given in Table 5.5-2 will permit some insight into the contribution of energy losses to heating (and cooling in the summer). The sources of energy loss considered are:

TABLE 5.5-1

ENERGY SAVINGS

Month	Solar Utilized (Million Btu)	Solar Energy Savings Attributable To (Million Btu)		Operating Energy (Million Btu)	Energy Savings (Million Btu)		Fossil Equivalent At Source (Million Btu)
		Space Heating	Domestic Hot Water		Electrical	Fossil	
Apr 78	1.62	1.14	1.49	0.35	-0.28	2.63	1.51
May 78	1.35	0.57	1.65	0.34	-0.28	2.22	1.10
Jun 78	0.72	0.07	1.13	0.42	-0.38	1.20	-0.32
Jul 78	1.05	0	1.75	0.38	-0.24	1.75	-0.79
Aug 78	1.22	0	2.03	0.35	-0.35	2.03	0.63
Sep 78	1.52	0.03	2.50	0.38	-0.41	2.53	0.81
Oct 78	1.52	0.68	1.80	0.35	-0.38	2.48	0.96
Nov 78	1.56	1.22	1.19	0.59	-0.28	2.41	1.29
Dec 78	1.74	1.83	0.95	0.43	-0.17	2.78	2.1
Jan 79	2.25	2.23	1.37	0.48	-0.18	3.60	2.88
Feb 79	2.98	3.30	1.36	0.59	-0.28	4.66	3.54
Mar 79	2.95	3.17	1.53	0.55	-0.29	4.70	3.54
Total	20.48	14.24	18.75	5.21	-3.52	32.99	17.33
Average	1.71	1.19	1.56	0.43	-0.29	2.75	1.44

TABLE 5.5-2

SYSTEM ENERGY LOSSES

Month	System Solar Loss (Million Btu)	System Solar Plus DHW Auxiliary Loss (Million Btu)	Estimated Loss Contribution To Heating (Million Btu)	Estimated Loss To Cooling Load (Million Btu)
Apr 78	5.68	6.09	6.09	0
May 78	5.95	5.98	2.50	3.47
Jun 78	6.59	6.67	1.33	5.34
Jul 78	7.33	7.44	0	7.44
Aug 78	7.33	7.36	0	7.36
Sep 78	6.53	6.53	2.83	3.70
Oct 78	5.70	5.88	5.88	0
Nov 78	3.22	3.55	3.55	0
Dec 78	1.33	1.89	1.89	0
Jan 79	0.93	1.56	1.56	0
Feb 79	2.67	3.09	3.09	0
Mar 79	3.82	4.31	4.31	0
Total	57.08	60.35	33.03	27.32

1) Collector to storage plumbing
2) Storage tank, plumbing and heat exchangers
3) DHW (Solar energy) plumbing and tank
4) DHW (Auxiliary energy) plumbing and tank.

The energy losses are uncontrolled energy in the sense that the home owner cannot demand the energy for heating or turn it off when it is undesired (cooling requirement). The home owner is not permitted, under his warranties, to discontinue the active circulation of the working solution in the collectors during periods of normal insolation levels. Nonetheless, the losses contribute to heating and cooling loads and to the savings for the year. In Table 5.5-2, the losses are identified. The contribution of the losses to heating or to cooling are based on prorating the loss, in a given month, based on the number of days in which cooling or heating took place. Cooling was identified by instrumentation in the furnace normally used to identify temperature change in the circulating air mass when energy was being added to the plenum. The negative temperature differential during blower operation identified cooling periods.

The estimated normal (controlled) heating plus the fossil equivalent of the losses attributable to heating is 72.4 million Btu (17.33 + 33.03/0.6). This equates to a savings of $190 versus $45 for controlled energy savings.

The cooling load equivalent to the energy losses in the months of May through September is estimated to be 27.32 million Btu (8,000 kwh). Assuming a standard COP for the air-conditioning unit of 2.5, 3,200 kwh of compressor/fan power were required. An average cost for electricity in Denver is four times the rate for natural gas (a graduated rate based on use). Based on 0.036 dollars per kwh, the cost (negative saving) of cooling was $115.20.

Giving credit for losses used in heating and subtracting the penalty for cooling during the summer months, the net savings for the 12-month period were $75 ($190 - $115). This prorates to $6.25 per month.

In summary, because the design intent is not fully understood relative to insulation versus uncontrolled losses, and the loss contribution to heating and cooling are estimated, the savings per month, on the average, lay between $3.78 and $6.25 per month.

A final comment is that reduction of losses by retrofitting the plumbing with insulation would increase the controlled energy and result in an improvement in the 58 percent solar fraction shown in Table 5.2-1.

6. REFERENCES

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8. "Electricity and Gas Consumption of 24 Solar Homes Compared with 26 Conventional Homes Having Identical Heating Loads," John C. Ward, Professor of Civil Engineering, Colorado State University, Conference Proceedings, Solar Heating and Cooling Systems Operational Results, Colorado Springs, Colorado, 28 November - 1 December 1978.

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

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.

- COLLECTOR REJECTED ENERGY (CSRJE) is the energy rejected intentionally from the energy collection and storage subsystem.

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 (ICSS) 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 aperature, 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.

DOMESTIC HOT WATER SUBSYSTEM

The domestic 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. 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 FOSSIL FUEL (HWAF) is the amount of fossil 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.

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.
- ELECTRICAL ENERGY SAVINGS (HSVE) 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.

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

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

ENVIRONMENTAL SUMMARY

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

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

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

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

where $\bar{C}_p$ 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 power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

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

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

EQUATIONS USED IN MONTHLY REPORT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

AVERAGE AMBIENT TEMPERATURE (°F)

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

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

FOR ± 3 HOURS FROM SOLAR NOON

AVERAGE BUILDING TEMPERATURE (°F)

$$TB = (1/60) \times \Sigma\ T301 \times \Delta\tau$$

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

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

INCIDENT SOLAR ENERGY (BTU/FT^2)

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

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

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

WHEN ECSS PUMPS ARE OPERATING

COLLECTED SOLAR ENERGY BY ARRAY (BTU)

$$SECA = \Sigma\ (T125 - T100) \times M100 \times CP23\ ((T125 + T100)/2) \times \Delta\tau$$

WHEN ECSS PUMPS ARE OPERATING AND T125 > T100

ECSS REJECTED ENERGY (BTU)

$$CSRFE = \Sigma\ (T100 - T125) \times M100 \times CP23\ ((T125 + T100)/2 \times \Delta\tau$$

WHEN ECSS PUMPS ARE OPERATING AND T100 > T125

ECSS OPERATING ENERGY (BTU)

$$CSOPE = 56.8833 \times \Sigma\ (EP100 + EP200) \times \Delta\tau$$

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

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 DELIVERED TO ECSS STORAGE (BTU)

$STEI = \Sigma\ (M200 \times HWD\ (T225,\ T200)) \times \Delta\tau$

WHEN T225 > T200

SOLAR ENERGY REJECTED FROM STORAGE (BTU)

$RFESTEO = \Sigma\ M200 \times HWD\ (T200,\ T225) \times \Delta\tau$

WHEN T200 > T225

ENERGY SUPPLIED BY ECSS STORAGE (BTU)

STEO = HWSE + HSE + RJESTEO

ENERGY SUPPLIED TO LOADS BY ECSS STORAGE (BTU)

SEL = HWSE + HSE

CHANGE IN STORED ENERGY IN SOLAR STORAGE (BTU)

$STECH = STOE_1 - STOE_2$

WHERE $STOE_1$ IS STORAGE ENERGY AT BEGINNING OF THE CURRENT HOUR AND $STOE_2$ IS THE STORAGE ENERGY AT THE BEGINNING OF THE PREVIOUS HOUR

ECSS STORAGE TANK EFFICIENCY (RATIO)

STEFF = [STEO + STECH + RJESTEO/STEI]

ECSS STORAGE TEMPERATURE (°F)

$TST = \Sigma\ (T300 + T302)/2 \times \Delta\tau$

DHW SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

HWSVF = (HWSE/HWHEFF)

WHERE HWHEFF = 0.6 (EFFICIENCY)

DHW SUBSYSTEM SOLAR FRACTION (PERCENT)

HWSFR = 100 x HWTKSE/(HWTKAUX + HWTKSE)

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

SERVICE HOT WATER CONSUMPTION (GALLONS)

HWCSM = Σ WD300 x $\Delta\tau$

WHERE WD300 IS THE FLOW, W300, MODIFIED BY LOGICAL EXPRESSIONS CONVERTING TOTALIZING FLOW METER DATA

SOLAR ENERGY TO DHW SUBSYSTEM (BTU)

HWSE = Σ (M300 x HWD (T328, T303)) x $\Delta\tau$

DHW AUXILIARY FOSSIL FUEL ENERGY (BTU)

HWAF = Σ (F300 x HWHCON) x $\Delta\tau$

WHERE F300 = F300 x K; K DETERMINED FROM ACTUAL MONTHLY GAS BILLING AND HWHCON = 700 (ENERGY CONVERSION FACTOR)

DHW AUXILIARY THERMAL ENERGY (BTU)

HWAT = (HWAF x HWHEFF)

WHERE HWHEFF = 0.6 (EFFICIENCY)

DHW SUBSYSTEM LOAD (BTU)

HWL = Σ M300 x HWD (T329, T303) x $\Delta\tau$

SUPPLY WATER TEMPERATURE (°F)

TSW = Σ (T303 x M300) x $\Delta\tau$/M300) x $\Delta\tau/\Sigma$ M300 x $\Delta\tau$

WHEN M300 > 0

SERVICE HOT WATER TEMPERATURE (°F)

$$THW = \Sigma\ (T329 \times M300) \times \Delta\tau / \Sigma\ M300 \times \Delta\tau$$

WHEN M300 > 0

HEATING SUBSYSTEM LOAD (BTU)

$$HL = \Sigma\ (HSE + HAT) \times \Delta\tau$$

HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$$HOPE = 56.8833 \times \Sigma\ (EP400 + EP401) \times \Delta\tau$$

HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

$$HSFR = 100 \times HSE/HL$$

SOLAR HEATING ELECTRICAL ENERGY SAVINGS (BTU)

$$HSVE = -56.8833 \times \Sigma\ EP400 \times \Delta\tau$$

SOLAR HEATING FOSSIL ENERGY SAVINGS (BTU)

$$HSVF = HSE/FEFF$$

HEATING SUBSYSTEM AUXILIARY FOSSIL ENERGY (BTU)

$$HAF = FCON \times \Sigma\ F400 \times \Delta\tau$$

WHERE FCON = 1666.69 (ENERGY CONVERSION FACTOR)

HEATING SUBSYSTEM AUXILIARY THERMAL ENERGY (BTU)

$$HAT = HAF \times FEFF$$

WHERE FEFF = 0.64 (EFFICIENCY)

SOLAR ENERGY TO HEATING SUBSYSTEM (BTU)

$$HSE = \Sigma\ [M400 \times HWD\ (T400,\ T425)] \times \Delta\tau$$

TOTAL SYSTEM LOAD (BTU)

$$SYSL = HWL + HL$$

SOLAR FRACTION OF SYSTEM LOAD

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

SYSTEM OPERATING ENERGY (BTU)

$$SYSOPE = CSOPE + HOPE$$

TOTAL ENERGY CONSUMED BY SYSTEM (BTU)

TECSM = SYSOPE + HWAF + HAF + SECA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HSVE - CSOPE

TOTAL FOSSIL ENERGY SAVINGS (BTU)

TSVF = HWSVF + HSVF

AUXILIARY THERMAL ENERGY TO LOAD SUBSYSTEMS (BTU)

AXT = HWAT + HAT

AUXILIARY FOSSIL FUEL ENERGY TO LOAD SUBSYSTEMS (BTU)

AXF = HAF + HWAF

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/FOSSIL

WHERE FOSSIL = AXF + SYSOPE x 3.33

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

SITE: PERL MACK 60. LOCATION: DENVER CO

ANALYST: R. WALKER FDRIVE NO.: 8.

COLLECTOR TILT: 30.26 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 39.80 (DEGREES) RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1337.	841.	0.62865	1.739	1462.	1088	0	30.
FEB	1801.	1128.	0.62644	1.475	1664.	902	0	33.
MAR	2401.	1530.	0.63736	1.247	1908.	868	0	37.
APR	3024.	1880.	0.62177	1.062	1996.	525	0	48.
MAY	3463.	2135.	0.61647	0.953	2035.	253	0	57.
JUN	3641.	2352.	0.64607	0.909	2138.	80	110	66.
JUL	3547.	2271.	0.64037	0.929	2109.	0	248	73.
AUG	3189.	2043.	0.64049	1.014	2071.	0	208	72.
SEP	2622.	1726.	0.65801	1.172	2022.	120	54	63.
OCT	1974.	1302.	0.65926	1.406	1830.	408	5	52.
NOV	1444.	885.	0.61267	1.650	1460.	768	0	39.
DEC	1211.	734.	0.60611	1.811	1329.	1004	0	33.

LEGEND:

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

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

KBAR ==> RATIO OF HBAR TO HOBAR.

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

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

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

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

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.