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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR SEECO LINCOLN, LINCOLN, NEBRASKA

Prepared by

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16. ABSTRACT

This report developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy is one of a series of reports describing the operational and thermal performance of a variety of solar systems installed in Operational Test Sites. The analysis used is based on instrumented system data monitored and collected for at least one full season of operation. The objective of the analysis is to report the long-term field performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The SEECO Lincoln Solar Energy System was designed by the Solar Engineering and Equipment Company (SEECO), Metairie (New Orleans), Louisiana to provide 60 percent of the space heating for the 50 seat Hyde Memorial Observatory in Lincoln, Nebraska. The system consists of nine SEECO Mod 1 flat plate air collectors (481 square feet), a 347 cubic foot rock storage bin, blowers, controls and air ducting. An auxiliary natural gas furnace provides additional energy when the solar energy is not adequate to meet the space heating demand. The system has five modes of operation. This report discusses system description, typical system operation, system operating sequence, performance assessment, system performance, subsystem performance (collector array, storage, space heating), operating energy, energy savings and maintenance. Page 46 presents the summary and conclusions of this solar system which became operational in December 1977.

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1. FOREWORD

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

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

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

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

The Seasonal Report document in conjunction with the Final Report for each Operational Test Site in the Development Program culminates the technical activities which began with the site selection and instrumentation system design in April 1976. The Final Report emphasizes the economic analysis of solar systems performance and features the payback performance based on life cycle costs for the same solar system in various geographic regions. Other documents specifically related to this system are References [1] and [2].

*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The Seeco Lincoln Solar Energy System provides space heating for the 50 seat Hyde Memorial Observatory in Lincoln, Nebraska. The energy collection and storage subsystem consists of 481 square feet of flat plate collectors with air as the transport medium and 347 cubic feet of rock storage. The collector azimuth is south and the tilt is 56° from horizontal. Solar heated air is supplied directly to the heated space or to rock storage. When solar energy is not adequate to meet the space heating demand, an auxiliary natural gas furnance provides the additional energy.

The system is shown schematically in Figure 2-1. The sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 [4]. The measurement symbol prefixes: W, T, EP, I and F represent respectively: flow rate, temperature, electric power, solar insolation and fossil fuel usage. Figure 2-2 is a pictorial view of the Seeco Lincoln solar installation.

The Solar Energy System has five operational modes which are described as follows:

<u>Mode 1 - Collector to Space</u>: This mode is initiated when there is a demand for space heating and absorber plate temperature is approximately 110°F and is hotter than a temperature that is representative of the top of rock storage. The collector fan and auxiliary furnace fan operate in series to supply solar heated air direct to the heated space. Circulation continues in this mode until the discharge air from the solar collectors is below 90°F or the demand for space heating is satisfied.

<u>Mode 2 - Storage to Space</u>: This mode is initiated when there is a demand for space heating and the absorber plate temperature is below 90°F and a temperature representative of the top of storage is higher than 90°F. The auxiliary furnance fan operates to supply air direct from rock storage to the heated space. Circulation continues in this mode until the demand for space heating is satisfied or the room temperature has fallen an additional 2°F below the original demand temperature setting and auxiliary heat is called for.

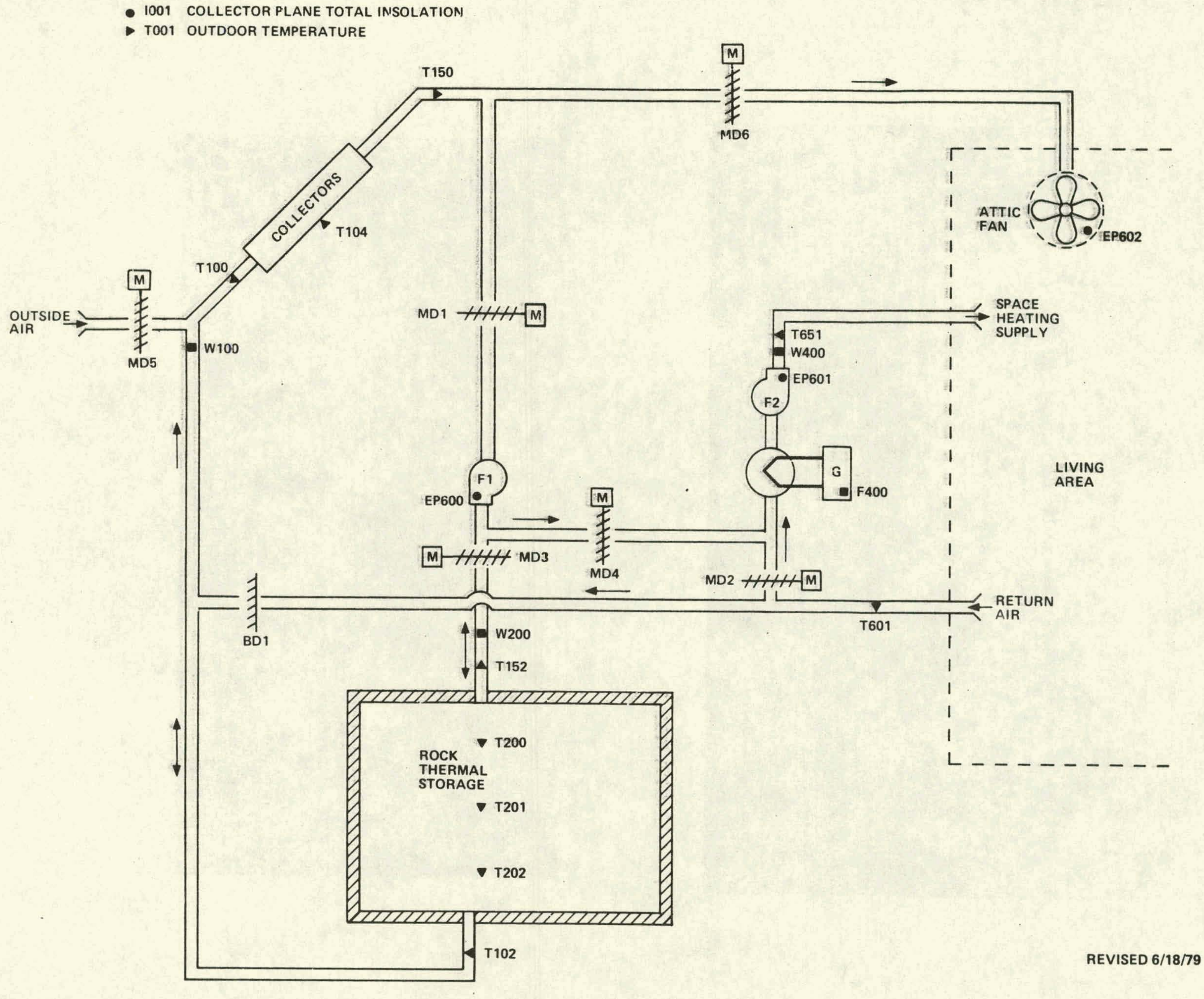

Figure 2-1 Seeco Lincoln Solar Energy System Schematic

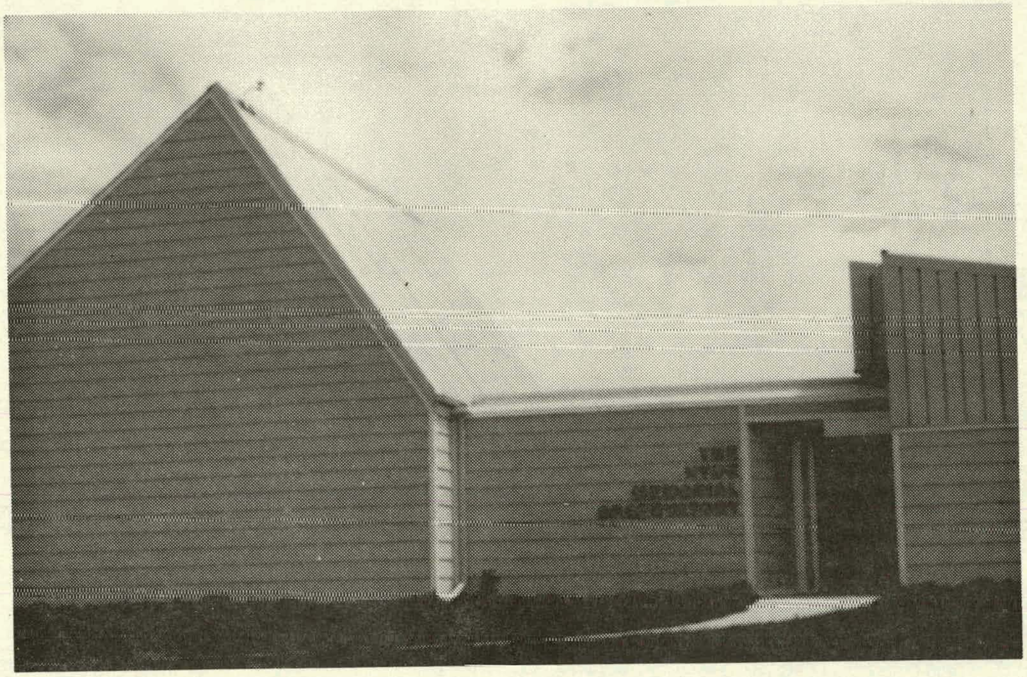

Figure 2-2 Seeco Lincoln Pictorial

Mode 3 - Collector to Storage: This mode is initiated when there is no demand for space heating and the absorber plate temperature is approximately 110°F and is hotter than a temperature representative of the top of rock storage. The collector fan operates to circulate air directly from the solar collectors to rock storage. This mode of operation continues until the absorber plate temperature is below 90°F or space heating is called for.

Mode 4 - Auxiliary Heat: This mode is initiated when there is a demand for space heating and the absorber plate temperature is below 90°F and the temperature representative of the top of rock storage is below 90°F or when solar heat is being supplied and the room temperature has fallen an additional 2°F below the original demand temperature setting. The auxiliary furnance fan operates to circulate air from the natural gas furnace to the room.

Mode 5 - Vent Mode: This mode is initiated by manually switching to the "summer mode" during the summer when the solar collection system is inoperative and the collector plate temperature reaches approximatley 200°F. In this mode outside air is circulated through the collectors by the attic fan to avoid summer stagnation temperatures which are potentially damaging to the collector.

2.1 Typical System Operation

Curves depicting typical system operation on a cold, bright day (February 26, 1980) are presented in Figure 2.1-1. Figure 2.1-1(a) shows the insolation on the collector array and the period when the array was operating (shaded area). Also shown in Figure 2.1-1(a) are the collector array temperature profiles. These are the inlet temperature (T100), the outlet temperature (T150) and the absorber plate temperature (T104).

On this particular day the collector began operating at 0926 hours. At that time the insolation level was 188 Btu/Ft^2-Hr and the absorber plate temperature (T104) was 103°F. At the same time the collector array inlet temperature (T100) was 54°F and array outlet temperature (T150) was 66°F.

The collector array continued to operate normally throughout the day. It will be noted that T104 tracked the insolation level quite closely during the operational period. The array outlet temperature (T150) also tracked both the insolation level and absorber plate temperature. The collector array inlet temperature (T100) showed a gradual rise throughout the operational period. This is expected because the system was operating in the collector-to-storage mode most of the day and, as a result, T100 tended to track the temperature at the bottom of the storage bin fairly closely.

The collector array continued to operate until 1715 hours when it shut down. At the time of collector turn-off, the absorber plate temperature had dropped to 118°F. At termination of collector loop operation the collector outlet temperature (T150) was 96°F and the inlet temperature (T100) was 76°F. This operation is generally compatible with the specified set point for collector turn-off at an air outlet air temperature of 90°F or less but it should be noted that T150 is a monitoring sensor only. The temperature seen by the actual control sensor could easily differ by several degrees due to sensor type and placement. The insolation level at collector turn-off was 72 Btu/Ft^2-Hr.

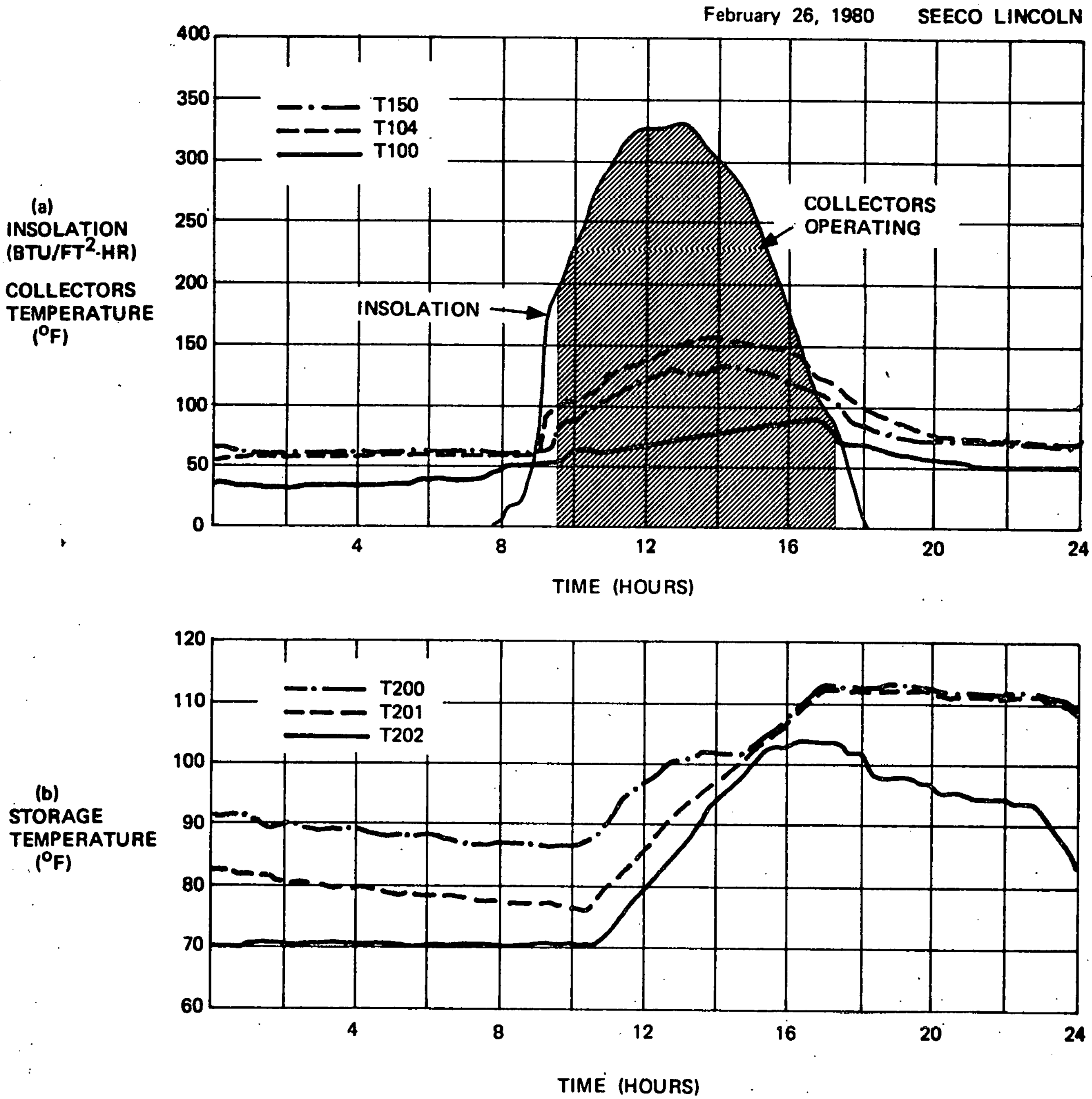

Figure 2.1-1 Typical System Operating Parameters - Seeco Lincoln

Figure 2.1-1(b) presents a profile of the rock storage bin temperatures for the selected day. Prior to the start of collector operation the furnace was providing energy for space heating because storage temperature was below the minimum level of 90°F. From collector turn-on at 0926 the system was alternately providing energy to the heated space and charging storage until about 1400 hours when it entered and remained in the storage charging mode for the remainder of the operational period. During the storage charging period the temperature profile exhibited the expected rise, throughout the period of collector operation, with the temperature at the top of storage reaching a maximum of 114°F at the time of collector turn-off. Once collector array operations, and hence, storage charging ceased, the system remained relatively stable for the rest of the day except for a marked decline in T202 (bottom of storage) which is attributed to a duct leak at the bottom of the storage bin. A small amount of heating from storage occured between 2200 and 2400 hours which is reflected in the slight decrease in storage temperatures during that interval.

2.2 System Operating Sequence

Figure 2.2-1 presents bar charts showing typical operating sequences for February 26, 1980. This data correlates with the curves presented in Figure 2.1-1 and provides some additional insight into those curves. This particular day was chosen because all possible modes of system operation (except the collector vent mode which is unique to summer months) were exercised at some time during the day.

As shown in Figure 2.2-1, the furnace was supplying the entire heating demand until the solar collection system became active at 0926 hours. From turn-on until approximately 1400 hours, the system alternated between the Collector-to-Space Heating and Collector-to-Storage modes. From 1400 hours until collector turn-off at 1715 hours operation was entirely in the storage charging mode. From 1800 hours until midnight the space heating demand was met by withdrawing energy from rock storage.

On the day selected to depict a typical operating sequence, the Seeco Lincoln Solar Energy System made a significant contribution to the heating requirements of the building. With an average outdoor temperature of 32°F, the solar system contributed 72,000 Btu to the space heating load and attained a solar fraction of 45 percent.

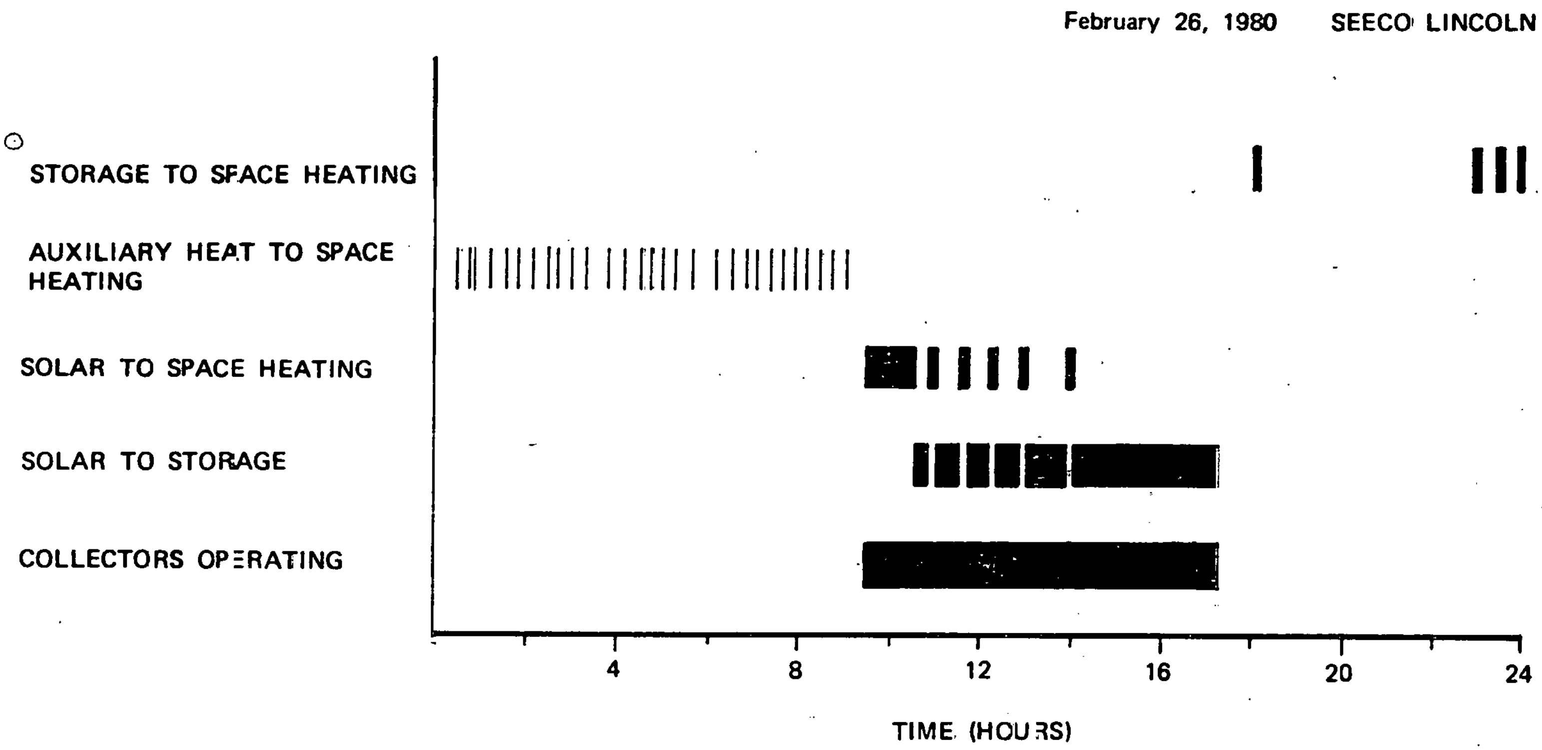

Figure 2.2-1 Typical System Operating Sequence - Seeco Lincoln

3. PERFORMANCE ASSESSMENT

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

3.1 System Performance

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

The measurement data were collected for the period April, 1979, through March, 1980. System performance data were provided through an IBM developed Central Data Processing System (CDPS) [3] consisting of a remote Site Data Acquisition System (SDAS), telephone data transmission lines and couplers, an IBM System 7 computer for data management, and an IBM System 370/145 computer for data processing. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. These data are processed daily and summarized into monthly performance formats which form a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data contained in this report.

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

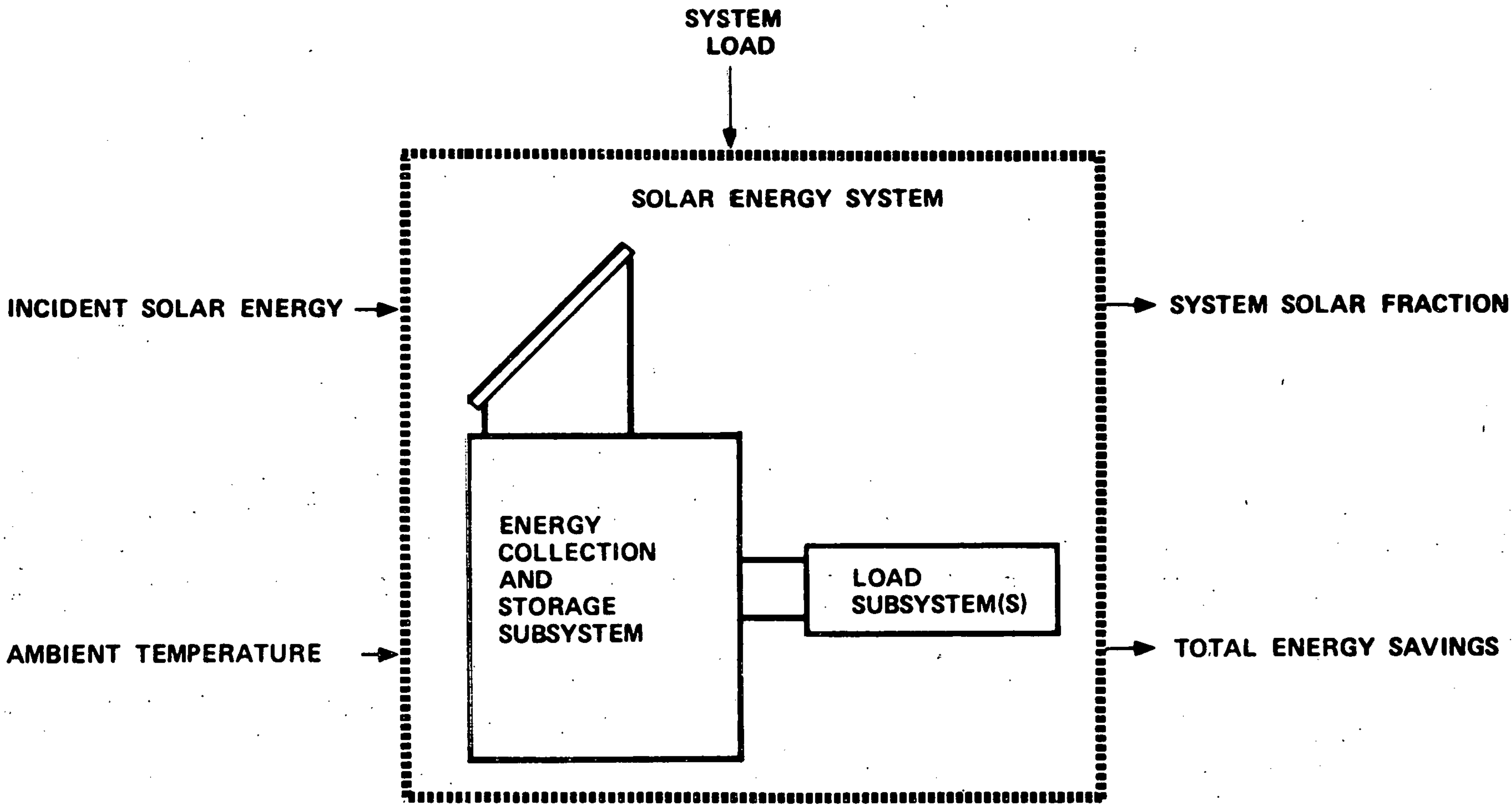

Figure 3.1-1 Solar Energy System Evaluation Block Diagram

Inputs

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

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

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

Outputs

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

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

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

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY

SEECO LINCOLN

Month	Daily Incident Solar Energy per Unit Area @ 56° Tilt (Btu/ft² Day)		Ambient Temperature °F		System Load-Measured (Million Btu)	Solar Fraction (Percent)		Total Energy Savings (Million Btu)
	Measured	Long Term Average	Measured	Long Term Average		Measured	Expected	
Apr 79	1325	1404	49	51	2.521	45	59	1.207
May 79	1342	1405	62	62	0.740	18	20	-0.297
Jun 79	1427	1429	73	72	0.000	0	100	-0.362
Jul 79	1147	1539	75	77	0.000	0	100	-0.212
Aug 79	1546	1519	76	76	0.000	0	100	-0.196
Sep 79	1331 *	1564	74	66	0.000	0	0	-0.289
Oct 79	1288 *	1552	57	55	0.449	0	0	-0.141
Nov 79	1209	1316	37	39	2.898	9	14	0.291
Dec 79	1212	1184	33	27	5.396	37	31	3.149
Jan 80	1070	1333	25	22	7.686	25	24	2.988
Feb 80	1011	1467	24	28	7.376	19	21	2.252
Mar 80	1393	1527	35	37	5.024	37	38	2.915
Total	15301	17239	--	--	32.090	--	--	11.305
Average	1275	1437	52	51	2.674	27 **	27	0.942

* Incident energy computed from average value of July, August, and November due to pyranometer and SDAS malfunctions in September and October, 1979.

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

At the Seeco Lincoln site for the twelve month report period, the long-term average daily incident solar energy in the plane of the collector was 1437 Btu/ft^2. The average daily measured value was 1275 Btu/ft^2 which is about 11 percent below the long-term value. On a monthly basis, February of 1980 was the worst month with an average daily measured value of incident solar energy 31 percent below the long-term average daily value. December, 1979, was the best month with an average daily measured value 2 percent above the long-term average daily value. On a long-term basis the measured value of incident solar energy was sufficiently below the long-term value to have a negative influence on the performance of the solar energy system.

The outdoor ambient temperature influences the operation of the solar energy system in two important ways. First the operating point of the collectors and consequently the collector efficiency or energy gain is determined by the difference in the outdoor ambient temperature and the collector inlet temperature. This will be discussed in greater detail in Section 3.2.1. Secondly the load is influenced by the outdoor ambient temperature. The measured average daily ambient temperature was 52°F for the Seeco Lincoln site which is 1°F above the long-term value of 51°F. On a monthly basis February of 1980 was the worst month, temperaturewise, when the measured temperature was 4°F below the long-term daily average. This below average temperature, in conjunction with a high heating load, had an adverse impact on system performance. The result was a decreased solar fraction which led to a decrease in the total net savings.

The effect of system load and ambient temperature on the performance of the Seeco Lincoln Solar Energy System can be seen by reference to Table 3.1-1. The maximum solar fraction of 45 percent was achieved in April, 1979, when system load was low and ambient temperature was only 2°F below the long-term average value. The lowest solar fraction during the heating season was recorded in November, 1979, (9%) and, in this case, the poor performance is attributed to the fact that the space heating fan (F2) which delivers solar heated air to the building in both the Collector-to-Space and Storage-to-Space modes was inoperative for most of the month.

Also presented in Table 3.1-1 are the measured and expected values of system solar fraction where system solar fraction is the ratio of solar energy applied to the system loads to the total energy (solar plus auxiliary) applied to the loads. The expected values have been derived from a modified f-Chart analysis which uses measured weather and subsystem loads as inputs (f-Chart is the designation of a procedure that was developed by the Solar Energy Laboratory, University of Wisconsin, Madison, for modeling and designing solar energy systems [8]). The model used in the analysis is based on manufacturers' data and other known system parameters. The bases for the model are empirical correlations developed for liquid and air solar energy systems that are presented in graphical and equation form and referred to as the f-Chart where 'f' is a designator for the system solar fraction. The output of the f-Chart procedure is the expected system solar fraction. The measured value of system solar fraction was computed from measurements obtained through the instrumentation system of the energy transfers that took place within the solar energy system. These represent the actual performance of the system installed at the site.

The total energy saving is an important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with less expensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment for the system. In terms of the technical analysis presented in this report the net total energy savings should be significant positive figure. The total net energy savings for the Seeco Lincoln Solar Energy System was 11.31 million Btu or 3312 kWh. This is equivalent to 1.9 barrels of oil.

3.2 Subsystem Performance

The Seeco Lincoln Solar Energy Installation may be divided into three subsystems:

1. Collector array
2. Storage
3. Space heating

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

3.2.1 Collector Array Subsystem

The Seeco Lincoln collector array consists of 9 Seeco Mod 1 flat-plate air collectors arranged in a single parallel row of 9 collectors. These collectors are a one-pass air heating type with a double glazing. Typical flowrate through the collector array is approximately 1.17 CFM per square foot of gross array area. Details of the air flow path are shown in Figure 3.2.1-1 (a) and a cross-sectional view of the collector panel is presented in Figure 3.2.1-1 (b). The collector subsystem analysis and data are given in the following paragraphs.

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

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

where η_c = Collector array efficiency

Q_s = Collected solar energy

Q_i = Incident solar energy

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

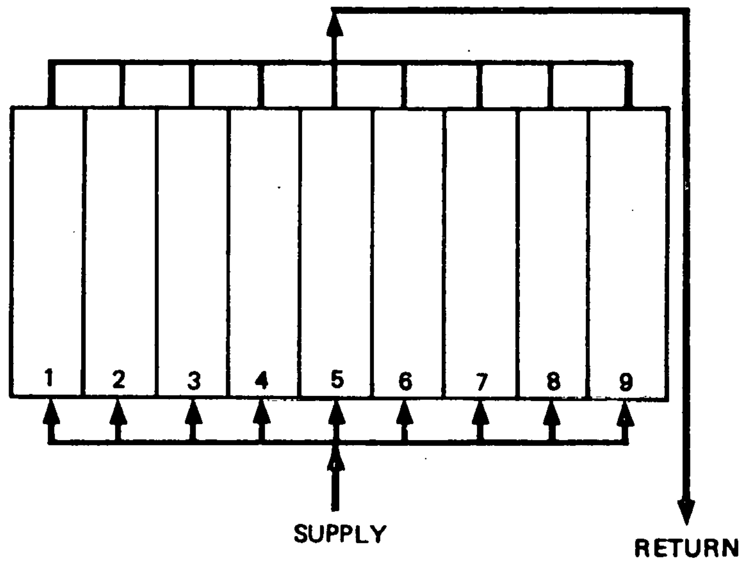

Figure 3.2.1-1(a). Collector Array Arrangement

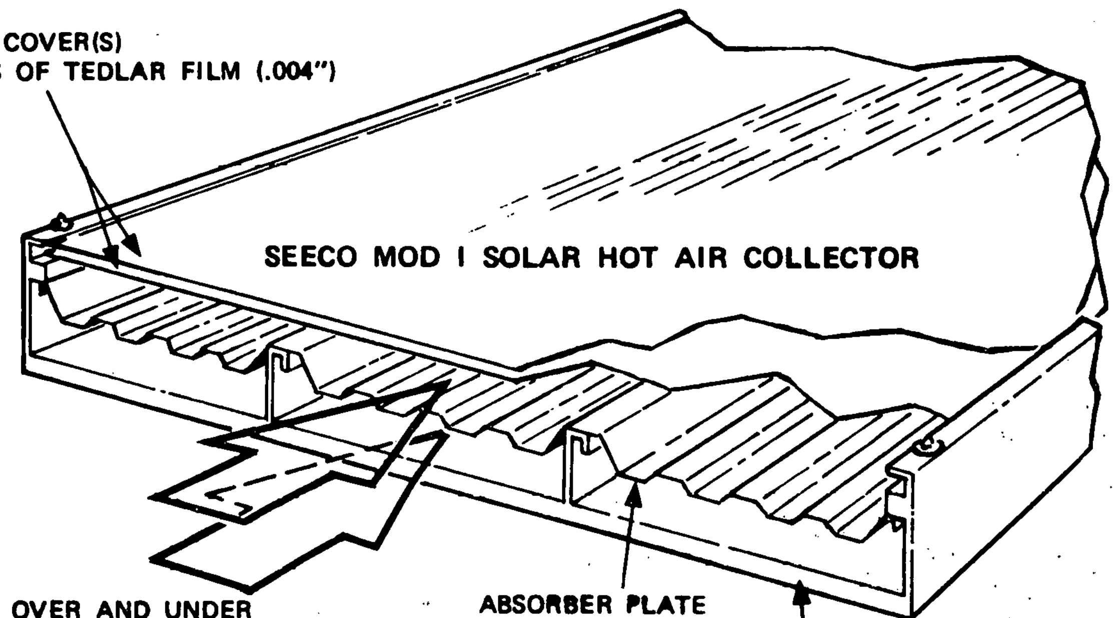

Figure 3.2.1-1(b). Collector Panel Air Flow Path

COLLECTOR DATA

Manufacturer – Solar Engineering & Equipment Co.
Model – SEECO MOD I
Type – Air
Number of Collectors – 9
Flow Paths – 9

SITE DATA

Location – Hyde Memorial Observatory
Lincoln, Nebraska
Latitude – 40.51° N
Longitude – 96.44° W
Collector Tilt – 56°
Azimuth – 0° (Due South)

Figure 3.2.1-1 Collector Array Schematic

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

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

where η_{co} = Operational collector array efficiency

Q_s = Collected solar energy

Q_{oi} = Operational incident solar energy

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

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

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

In the ASHRAE Standard 93-77 [5] a collector efficiency is defined in the same terminology as the operational collector array efficiency. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector array efficiency is determined from actual dynamic conditions of daily solar energy system operation in the field.

TABLE 3.2.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Array Efficiency
Apr 79	19.130	4.137	0.22	13.773	0.30
May 79	20.020	2.760	0.14	10.417	0.26
Jun 79	20.605	0.000	0.00	0.015	0.00
Jul 79	17.117	0.000	0.00	0.000	0.00
Aug 79	23.060	0.000	0.00	0.000	0.00
Sep 79	19.212[Note 1,2]	0.000	0.00	0.000	0.00
Oct 79	19.212[Note 1,2]	4.803[Note 1,3]	0.25	13.833[Note 1,4]	0.35
Nov 79	17.460	3.167	0.18	11.006	0.29
Dec 79	18.077	5.939	0.33	15.667	0.38
Jan 80	15.968	4.992	0.31	13.149	0.38
Feb 80	14.103	3.838	0.27	9.608	0.40
Mar 80	20.777	6.231	0.30	16.406	0.38
Total	224.741	35.891	--	103.919	--
Average	18.728	2.991	0.16	8.660	0.35

Notes:

1. Derived data due to SDAS and pyranometer malfunctions in September and October
2. Incident solar energy computed from average value of July, August and November
3. Collected solar energy derived using average ratio; $\frac{\text{Collected Solar Energy}}{\text{Incident Solar Energy}}$ for full report period
4. Operational incident solar energy derived using average ratio; $\frac{\text{Operational Incident Energy}}{\text{Incident Solar Energy}}$ for full report period.

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

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

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

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

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

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

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

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

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

$$x_j = \frac{T_i - T_a}{I} \tag{3}$$

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

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

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

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

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

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

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

b = Intercept on the efficiency axis

$(-)m$ = Slope

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

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

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

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

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

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

$$b = F_R(\tau\alpha) \tag{6}$$

and

$$m = F_R U_L$$

where the terms are as previously defined

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

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

The long-term first order curve presented in Figure 3.2.1-2 indicates that the collector array as a whole seemed to perform more poorly than the laboratory test unit. This is probably due to the fact that the performance of the collector array is influenced by the leakage of air from the array to a greater extent than from a single panel. Also the long-term first order curve has a much more negative slope than the curve derived from single panel laboratory test data. This is attributable to higher losses, prinicipally leakage, resulting from array mechanical interconnections. The laboratory predicted instantaneous efficiency is not in close agreement with the curve derived from actual field operation. This indicates that the laboratory derived curve might not be useful for design purposes in an array configuration of this type. However, this statement must be tempered by the fact that actual performance might approach predicted performance more closely if there were no leakage problems with the collector array or ductwork.

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

Single panel laboratory data

$F_R(\tau\alpha) = 0.600$ $\qquad F_RU_L = -1.375$

Long-term field data

$F_R(\tau\alpha) = 0.666$ $\qquad F_RU_L = -2.265$

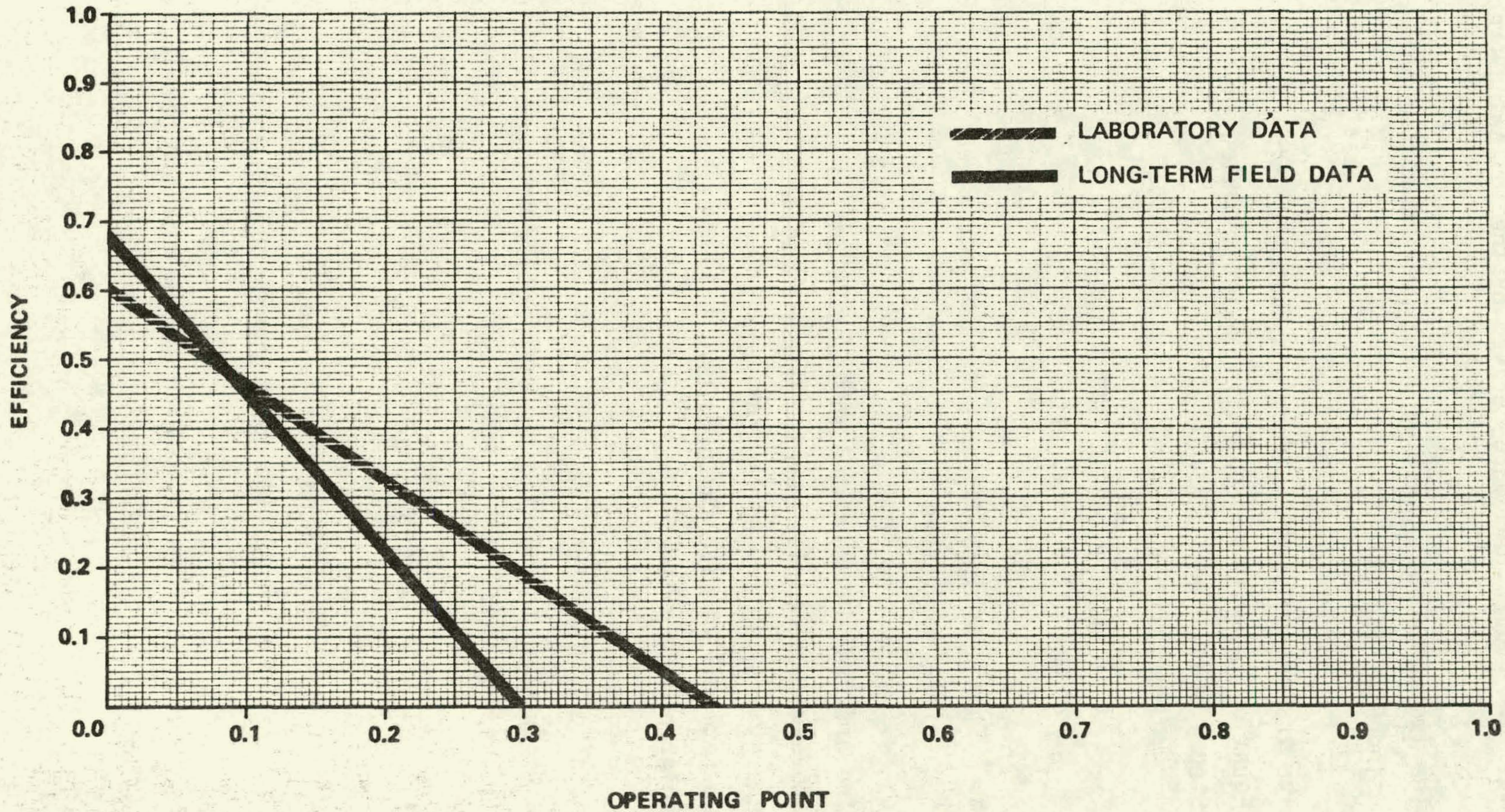


Figure 3.2.1-2 Seeco Lincoln Collector Efficiency Curves

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

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

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

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

    b. The laboratory single panel collector efficiency curve

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

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

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

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

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

TABLE 3.2.1-2

ENERGY GAIN COMPARISON

(ANNUAL)

SITE: Seeco Lincoln　　　　Lincoln, Nebraska

Month	Collected Solar Energy (Million Btu)	Error	
		Field Derived Long-Term	Laboratory Single Panel
Apr 79	8.066	0.117	-0.025
May 79	3.160	0.096	-0.053
Jun 79	(1)	(1)	(1)
Jul 79	(1)	(1)	(1)
Aug 79	(1)	(1)	(1)
Sep 79	(1)	(1)	(1)
Oct 79	1.275	0.024	-0.098
Nov 79	3.645	0.084	0.034
Dec 79	6.716	0.046	0.245
Jan 80	(2)	(2)	(2)
Feb 80	3.251	0.040	0.342
Mar 80	8.344	0.016	0.279
Average	4.922	0.063	0.144

Notes:
(1) System in summer vent mode - no energy collected
(2) Measurement failure

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

The data from Table 3.2.1-2 illustrates that, for the Seeco Lincoln site, the average error computed from the difference between the measured solar energy collected and the predicted solar energy collected based on the field derived long-term collector array efficiency curve was 6.3 percent. For the curve derived from the laboratory single panel data, the error was 14.4 percent. Thus the long-term collector array efficiency curve gives significantly better results than the laboratory single panel curve.

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

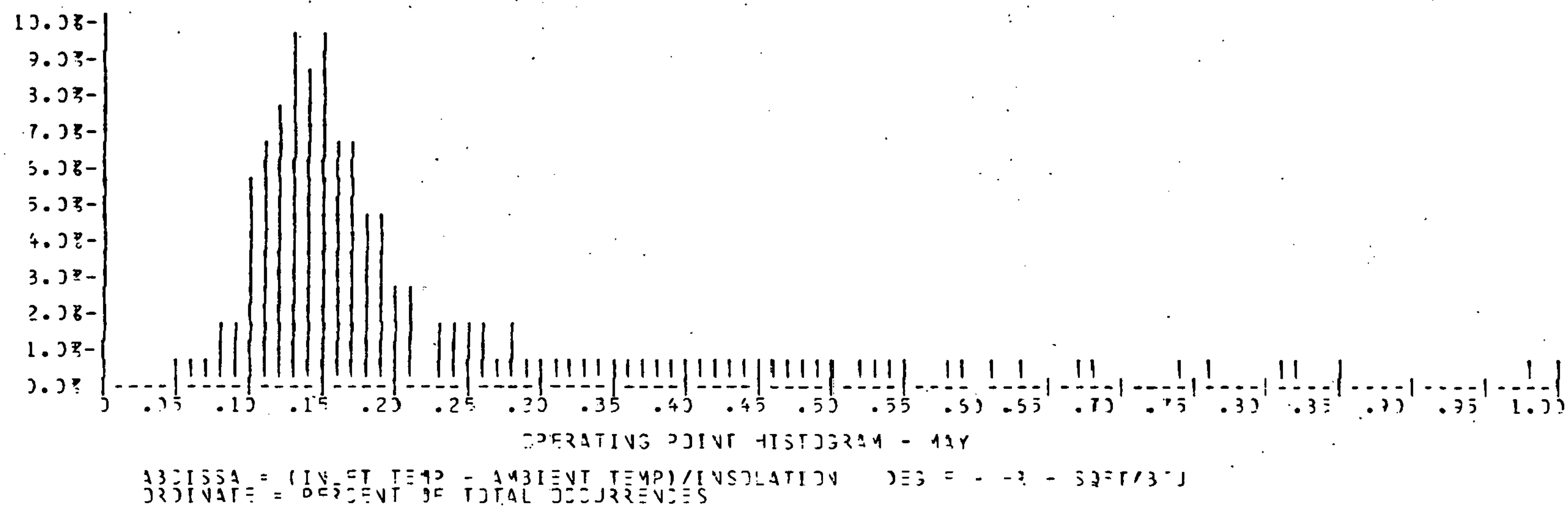
Another characteristic of the operating point histogram is the shifting of the distribution along the operating point axis. This can be explained in terms of the characteristics of the system, the climatic factors of the site, i.e., incident solar energy and ambient temperature, and the method of system operation. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (December) and a typical summer month (May) operation. The approximate average operating point for December is at 0.13 and for May at 0.15. In terms of Equation (3), it can be seen that, as the operating point becomes larger, the collector array efficiency decreases.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the 12 month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equations (1) and (2). On the average the operational collector array efficiency exceeded the collector array efficiency, which included the effect of the control system, by 47 percent.

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

SEECO - LINCOLN LINCOLN, NEBRASKA

COLLECTOR TYPE: SEECO COLLECTOR MODEL:



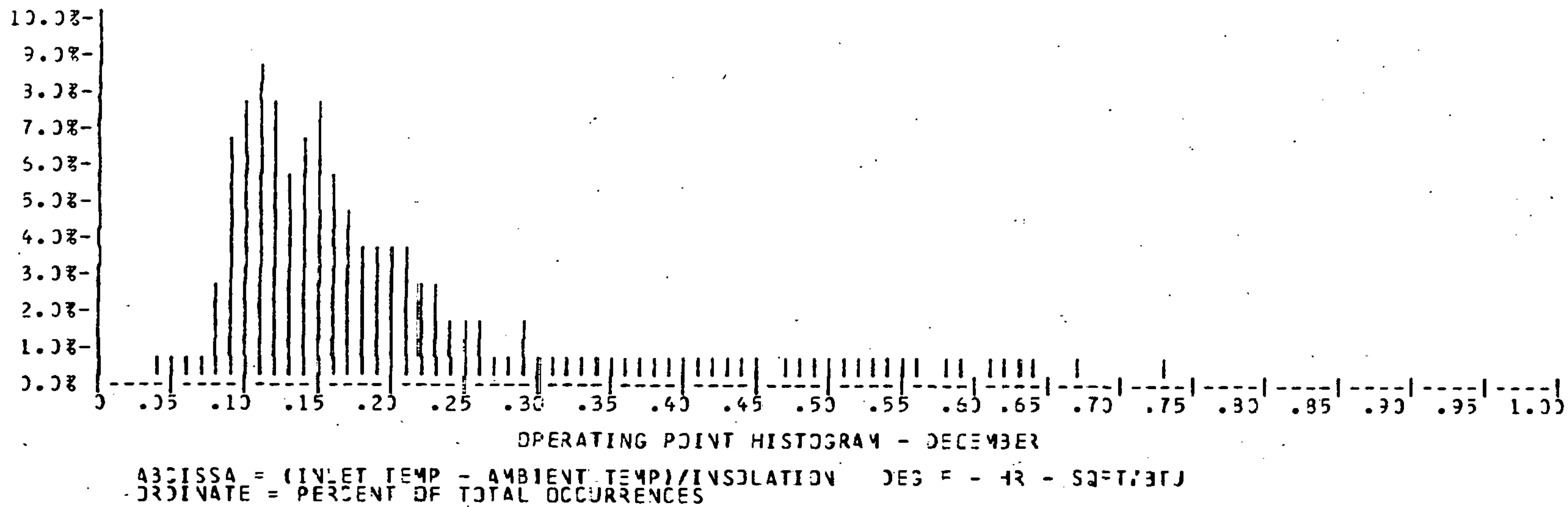


Figure 3.2.1-3 Seeco Lincoln Operating Point Histograms for Typical Winter and Summer Months

3.2.2 Storage Subsystem

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

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

where:

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

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

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

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

Table 3.2.2-1 summarizes the storage subsystem performance during the report period. Because the Seeco Lincoln solar energy system is a "heating only" system, the storage subsystem was essentially inactive during the warm weather months of June through September, 1979. For this reason, the evaluation of the storage subsystem was confined to the eight month period (April and May, 1979 and October, 1979, through March, 1980) when the storage subsystem was supplying energy to the space heating load.

For these eight months of active storage subsystem operation, an approximate total of 18.04 million Btu was delivered to storage and 4.31 million Btu was utilized for support of the space heating load. During this eight month period the net change in stored energy was 0.61 million Btu and the average storage efficiency was 0.30. The average storage temperature was 90°F over the eight month active period and 83°F over the full report period.

Although storage losses were not measured directly, they were estimated to be approximately 13.12 million Btu over the eight month active period for storage. This amounts to slightly over three times the measured energy supplied from storage and leads to the conclusion that performance of the storage subsystem was significantly degraded by excessive heat losses from the storage bin and transport ducts. It should be noted, however, that an undetermined percentage of these losses would enter the heated space and thereby reduce, to some extent, the amount of conventional energy required to maintain the comfort level of the building.

TABLE 3.2.2-1

STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)
Apr 79	3.149	1.084	0.325	0.448	97
May 79	1.949	0.122	-0.337	-0.110	112
Jun 79	0.000	0.000	-0.102	1.000	73
Jul 79	0.019	0.000	-0.027	1.000	69
Aug 79	0.000	0.000	-0.001	1.000	68
Sep 79	0.000	0.000	0.003	1.000	67
Oct 79	0.749	0.002	0.655	0.877	74
Nov 79	2.355	0.120	-0.072	0.021	96
Dec 79	2.901	1.041	-0.132	0.313	90
Jan 80	2.027	0.523	0.105	0.310	81
Feb 80	1.761	0.468	-0.116	0.200	78
Mar 80	3.149	0.951	0.185	0.361	93
Total	18.040 *	4.311 *	0.613 *	--	--
Average	2.255 *	0.539 *	0.077 *	0.303 *	90 *

* These values based only on the eight months that the storage system was active. The values for June, July, August, and September are not included in the totals or averages.

3.2.3 Space Heating Subsystem

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

The performance of the Seeco Lincoln space heating subsystem is presented in Table 3.2.3-1. For the 12 month period from April, 1979, through March, 1980, the solar energy system supplied a measured total of 8.73 million Btu to the space heating load. The total measured heating load for this period was 32.09 million Btu and the average monthly solar fraction was 27 percent.

The 27 percent solar fraction may be somewhat conservative because of the energy required for continuous operation of the pilot light in the gas furnace. Energy to the pilot light is not separately measured but an auxiliary energy demand of 0.5 million Btu per month is considered a reasonable estimate. The assumption that the pilot light operated continuously for the six primary heating months (April, 1979 and November, 1979, through March, 1980) results in the conclusion that the pilot light consumed 3.0 million Btu and, therefore, reduced the actual heating load from the measured value of 32.09 million Btu to 29.09 million Btu. On this basis, the solar fraction would increase from 27 percent to 30 percent.

During the 12 month reporting period, a total of 24.09 million Btu of auxiliary energy was supplied to the space heating load. Using an efficiency of 60 percent for the gas-fired furnace, the energy input to the auxiliary source was 40.15 million Btu, as shown in Table 3.2.3-1.

TABLE 3.2.3-1

HEATING SUBSYSTEM PERFORMANCE

Month	Heating Parameters			Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
	Load (Million Btu)	Temperatures (°F)			Auxiliary Thermal	Auxiliary	
		Building	Outdoor	Solar			
Apr 79	2.521	69	49	1.140	1.169	1.948	45
May 79	0.740	73	62	0.132	0.608	1.013	18
Jun 79	0.000	76	73	0.000	0.508 **	0.847 **	0
Jul 79	0.000	78	75	0.000	0.431 **	0.719 **	0
Aug 79	0.000	78	76	0.000	0.009 **	0.014 **	0
Sep 79	0.000	77	74	0.000	0.000	0.000	0
Oct 79	0.449	67	57	0.001	0.448	0.747	0
Nov 79	2.898	65	37	0.266	2.632	4.386	9
Dec 79	5.396	66	33	2.006	3.390	5.649	37
Jan 80	7.686	65	25	1.896	5.790	9.649	25
Feb 80	7.376	65	24	1.425	5.951	9.919	19
Mar 80	5.024	66	35	1.866	3.158	5.263	37
Total	32.090	--	--	8.732	24.094	40.154	--
Average	2.674	70	52	0.728	2.008	3.346	27 *

* Average solar fraction is the ratio of Total Solar Energy to Total Load

**Auxiliary Thermal Energy is due to pilot light in gas furnace.

4. OPERATING ENERGY

Operating energy for the Seeco Lincoln 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 (ECSS) operating energy, operating energy for the attic fan, when operating in the vent (summer) mode and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Table 4-1.

Operating energy for the Seeco Lincoln Solar Energy system is comprised of the electrical energy required to operate fan, F1 in the collector-to-storage loop, fan, F2 in the collector/storage-to-space heating loop and the attic fan in the vent mode loop. These are shown as EP600, EP601, and EP602, respectively, in Figure 2-1. Although additional electrical energy is required to operate motor driven dampers and the control system for the installation, it is not included in this report. These devices are not monitored for power consumption and the power they consume is insignificant, when compared to the fan motors.

TABLE 4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Vent Mode Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Apr 79	0.693	0.000	0.229	0.922
May 79	0.406	0.110	0.028	0.544
Jun 79	0.000	0.362	0.000	0.362
Jul 79	0.001	0.212	0.000	0.213
Aug 79	0.000	0.196	0.000	0.196
Sep 79	0.000	0.289	0.000	0.289
Oct 79	0.035	0.103	0.003	0.141
Nov 79	0.151	0.000	0.060	0.211
Dec 79	0.195	0.000	0.168	0.363
Jan 80	0.172	0.000	0.220	0.392
Feb 80	0.124	0.000	0.188	0.312
Mar 80	0.194	0.000	0.143	0.337
Total	1.971	1.272	1.039	4.282
Average	0.164	0.106	0.087	0.357

During the 12 month reporting period, a total of 4.28 million Btu (1253 kwh) of operating energy was consumed. However, this energy includes that portion of the energy required by fan, F2 when the fan is distributing air to the heated space (space heating operating energy) and that energy would be required whether or not the solar energy system was present. Therefore, this component of the operating energy is not considered "solar peculiar."

A total of 3.24 million Btu (950 kwh) of operating energy was required to support the fans when the solar collection, storage and summer vent subsystems were active. Of this total, however, only 1.97 million Btu are chargeable to the delivery of solar energy to the heating load because the 1.27 million Btu required for the attic fan is used solely for cooling the collectors in summer months, when no heating load is present. Thus, since a measured 8.73 million Btu of solar energy was delivered to the space heating load during the reporting period, a total of 0.23 million Btu (67 kwh) of operating energy was required for each one million Btu of solar energy delivered to the system load.

5. ENERGY SAVINGS

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystem is subtracted from the solar energy contribution to obtain the net savings attributed to the use of solar energy.

Energy savings for the 12 month reporting period are presented in Table 5-1. The gross savings in fossil energy was 14.55 million Btu which, when adjusted to account for the 3.24 million Btu of ECSS and vent mode operating energy, gave a net fossil energy savings of 11.31 million Btu (3312 kwh). This is equivalent to 1.9 barrels of oil.

TABLE 5-1

ENERGY SAVINGS

Month	Fossil Energy Savings (Million Btu) Space Heating	ECSS & Vent Mode Operating Energy (Million Btu)	Net Energy Savings (Million Btu)	Net Energy Savings (kwh)
Apr 79	1.900	0.693	1.207	353
May 79	0.220	0.516	-0.296	-87
Jun 79	0.000	0.362	-0.362	-105
Jul 79	0.000	0.213	-0.213	-62
Aug 79	0.000	0.196	-0.196	-57
Sep 79	0.000	0.289	-0.289	-85
Oct 79	0.002	0.138	-0.136	-40
Nov 79	0.443	0.151	0.292	85
Dec 79	3.344	0.195	3.149	922
Jan 80	3.160	0.172	2.988	875
Feb 80	2.376	0.124	2.252	659
Mar 80	3.109	0.194	2.915	854
Total	14.554	3.243	11.311	3312
Average	1.213	0.270	0.943	276

6. MAINTENANCE

This section provides a summary of all known maintenance visits made to the Seeco Lincoln site from the time it went "on line" until the closing of the data assessment period.

January 15, 1979

- Repaired furnace fan

February 2-6, 1979

- Repaired outside air leak

February 26 - March 2, 1979

- Sealed numerous leaks primarily in collector inlet plenum and top of rock storage chamber
- Replaced deteriorating vinyl duct tape with aluminum tape and repaired numerous minor leaks in duct seams and connections
- Repaired motorized damper MD2 to correct problem of incomplete closure
- Replaced two separate thermostats (one for solar system and one for auxiliary heat) with one two stage unit thus correcting system control problems
- Performed remapping of all system air flows at conclusion of leak repairs

April 2, 1979

- Repaired additional air leak causing large collector flow when operating in Storage-to-Load mode

November 28, 1979

- Repaired furnace fan controls

7. SUMMARY AND CONCLUSIONS

The following paragraphs provide a brief summary of all pertinent parameters for the Seeco Lincoln Solar Energy System for the period from April, 1979, through March, 1980. A more detailed discussion can be found in the preceding sections.

During the reporting period, the measured daily average insolation in the plane of the collector array was 1275 Btu/ft^2. This was 11 percent below the long-term daily average of 1437 Btu/ft^2. During the same period, the measured average outdoor ambient temperature was 52°F. This was one degree above the long-term average value of 51°F. Since the measured temperature was almost identical to the long-term average, this parameter had no impact on system performance. However, the lowered value of solar insolation, compared to the long-term average, had some degrading effect on performance for the overall report period.

The Solar Energy System satisfied 27 percent of the measured space heating load during the 12 month reporting period. This value was identical to the expected solar fraction obtained by the f-Chart analysis, on a yearly basis, but there was an average 15 percent variation between f-Chart and measured values on a month-by-month basis. The f-Chart value was higher than the measured value for five months of the seven month heating period but was exceeded by the measured value in the months of December, 1979, and January, 1980.

A total of 224.74 million Btu was measured in the plane of the collector array during the reporting period. The system collected 35.89 million Btu of the available energy, which represents a collector array efficiency of 16 percent. During periods when the collector array was active, a total of 103.92 million Btu was measured in the plane of the collector array. Therefore, the operational collector efficiency was 35 percent.

During the reporting period a total of 18.04 million Btu was delivered to the storage bin. During the same time 4.31 million Btu were removed from storage for support of the space heating load. In the period from June, 1979, through September, 1979, there was no heating load; hence, the storage subsystem was inactive during this period. For this reason, the computation of storage efficiency was based on the eight month period (October through May) when energy from storage was used to support a heating load. On this basis, the storage efficiency was computed to be 30 percent. During this time period, the net change in stored energy was 0.613 million Btu and an estimated 13.12 million Btu were lost from storage. The average storage temperature was 90°F over the eight month active heating period.

The measured space heating load was 32.09 million Btu for the 12 month reporting period. The heating solar fraction for the 12 month period was 27 percent, identical to the overall solar fraction because Seeco Lincoln is a "heating only" system. Solar energy supplied 8.73 million Btu and the gas furnace supplied 24.09 million Btu of auxiliary thermal energy. The space heating subsystem maintained an average building temperature of 70°F during the report period.

A total of 3.24 million Btu, or 950 kwh, of electrical operating energy was required to support the Seeco Lincoln Solar Energy System during the 12 month reporting period. The "solar unique" operating energy was comprised of 1.97 million Btu for the Energy Collection and Storage Subsystems (ECSS) and 1.27 million Btu for operation of the attic fan when operating in the summer vent mode.

The net fossil energy savings for the 12 month report period was 11.31 million Btu, or the equivalent of 3312 kWh, or 1.9 barrels of oil. It should be noted that the energy savings are based only on the measured amount of solar energy delivered to the space heating subsystem. The system losses into the heated space from the storage bin and ductwork were significant and, if they could be quantified, would add appreciably to the savings contributed by the Solar Energy System.

8. REFERENCES

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS

AND

SOLAR TERMS

APPENDIX A
DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

ENERGY COLLECTION AND STORAGE SUBSYSTEM

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

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

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

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

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

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

COLLECTOR ARRAY PERFORMANCE

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

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

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

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

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

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.

SPACE HEATING SUBSYSTEM

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

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.
- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.
- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.
- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.
- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.
- AUXILIARY FOSSIL FUEL (HAF) is the amount of fossil energy supplied directly to the subsystem.
- FOSSIL ENERGY SAVINGS (HSVF) is the estimated difference between the fossil energy requirements of an alternative conventional system (carrying the full load) and the actual fossil energy required by the subsystem.

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

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

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

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the Development Program. It is tabulated in this report for two purposes (1) as a measure of the conditions prevalent during the operation of the system at the site, and (2) as a historical record of weather data for the vicinity of the site.

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

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

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

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR

SEECO LINCOLN

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR SEECO LINCOLN

I. INTRODUCTION

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

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

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

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

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

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

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

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

For a liquid system ΔH is generally given by

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

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

For an air system ΔH is generally given by

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

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

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

For electrical power, a general example is

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

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

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

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

II. PERFORMANCE EQUATIONS

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

EQUATIONS USED IN MONTHLY PERFORMANCE ASSESSMENT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

AVERAGE AMBIENT TEMPERATURE (°F)

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

AVERAGE BUILDING TEMPERATURE (°F)

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

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

FOR $\pm$ 3 HOURS FROM SOLAR NOON

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

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

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

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

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

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

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

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$SECA = \Sigma$ [(M100 x (T150 - T100 + 10.0 x HRF) x $\Delta\tau$

SOLAR ENERGY TO LOAD FROM COLLECTOR ARRAY (BTU)

CSE01 = Σ [M400 x HRF x (T651 - T601)] x $\Delta\tau$

WHEN HEATING FROM THE COLLECTOR ARRAY

SOLAR ENERGY TO LOAD FROM STORAGE (BTU)

STEO = Σ [M400 x HRF x (T651 - T601] x $\Delta\tau$

WHEN HEATING FROM STORAGE

SOLAR ENERGY TO SPACE HEATING SUBSSYTEM (BTU)

HSE = CSE01 + STEO

WHENEVER THE SYSTEM IS HEATING FROM COLLECTORS OR STORAGE

HEATING AUXILIARY THERMAL ENERGY TO LOAD (BTU)

HAF = F400C x 1000.0

HAT = HAF x 0.6

WHEN HEATING FROM THE AUXILIARY SOURCE

SPACE HEATING LOAD (BTU)

HL = HSE + HAT

WHENEVER THE SYSTEM IS IN A SPACE HEATING MODE

AVERAGE TEMPERATURE OF STORAGE (°F)

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

SOLAR ENERGY TO STORAGE (BTU)

STEI = Σ [M200 x HRF x (T152 - T102)] x $\Delta\tau$

WHEN THE SYSTEM IS IN A STORING HEAT MODE

ECSS OPERATING ENERGY (BTU)

CSOPE = $56.8833 \times \Sigma \text{ EP600} \times \Delta\tau$

WHEN THE SYSTEM IS IN A STORING HEAT MODE OR HEATING FROM COLLECTORS MODE

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

HOPE = $56.8833 \times \Sigma \text{ EP601} \times \Delta\tau$

AUXILIARY FOSSIL FUEL ENERGY TO OIL FIRED FURNACE (BTU)

HAF = F400C x 1000.0

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

SEA = CLAREA x SE

COLLECTED SOLAR ENERGY PER UNIT AREA (BTU/FT^2)

SEC = SECA/CLAREA

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

CHANGE IN STORED ENERGY (BTU)

STECH = ROCKF x (TSTL - TSTLO)

WHERE ROCKF = 346.875 FT^3 x 165 LB/FT^3 x 0.2 BTU/LB - °F x (1 - 0.42 VOID) AND TSTL AND TSTLO ARE PRIOR REFERENCE VALUES

STORAGE EFFICIENCY

STEFF = (STECH + STEO)/STEI

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

CSEO = HSE

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

HSFR = 100 x HSE/HL

SPACE HEATING SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

HSVF = HSE/GEFF

WHERE GEFF IS THE GAS FURNACE EFFICIENCY = 0.6

SYSTEM LOAD (BTU)

SYSL = HL

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

SFR = HSFR

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = CSOPE + HOPE + SP103

WHERE SP103 IS THE ATTIC FAN ENERGY USED FOR SUMMER VENTING OF THE COLLECTORS

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HAT

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

SEL = HSE

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = CSEO/SEA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = -CSOPE - SP103

TOTAL FOSSIL ENERGY SAVINGS (BTU)

TSVF = HSVF

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXF + SECA

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXT + SYSOPE) x 3.33

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

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

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

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

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

SITE: SEECU LINCOLN 102.

LOCATION: LINCOLN NE

ANALYST: S. PATRICK

FDRIVE NO.: 59.

COLLECTOR TILT: 56.00 (DEGREES)

COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATTITUDE: 40.85 (DEGREES)

RUN DATE: 4/19/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1281.	675.	0.52678	1.976	1333.	1327	0	22.
FEB	1749.	933.	0.53347	1.573	1467.	1039	0	28.
MAR	2359.	1257.	0.53307	1.214	1527.	884	0	37.
APR	2999.	1497.	0.49909	0.938	1404.	419	8	51.
MAY	3455.	1777.	0.51432	0.791	1405.	166	73	62.
JUN	3642.	1954.	0.53648	0.731	1429.	22	232	72.
JUL	3544.	2043.	0.57634	0.753	1539.	0	386	77.
AUG	3171.	1740.	0.54873	0.873	1519.	9	333	76.
SEP	2587.	1423.	0.55020	1.099	1564.	33	101	66.
OCT	1925.	1066.	0.55353	1.457	1552.	329	15	55.
NOV	1389.	715.	0.51498	1.840	1316.	780	0	39.
DEC	1154.	571.	0.49525	2.072	1184.	1169	0	27.

LEGEND:

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

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

KBAR ==> RATIO OF HBAR TO HOBAR.

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

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

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

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

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

REFERENCES

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

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

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

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

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