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SOLAR/2032-83/14
(DE83012770)

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

UNIVERSITY OF MINNESOTA BOOKSTORE
Minneapolis, Minnesota
April 1982 through August 1982
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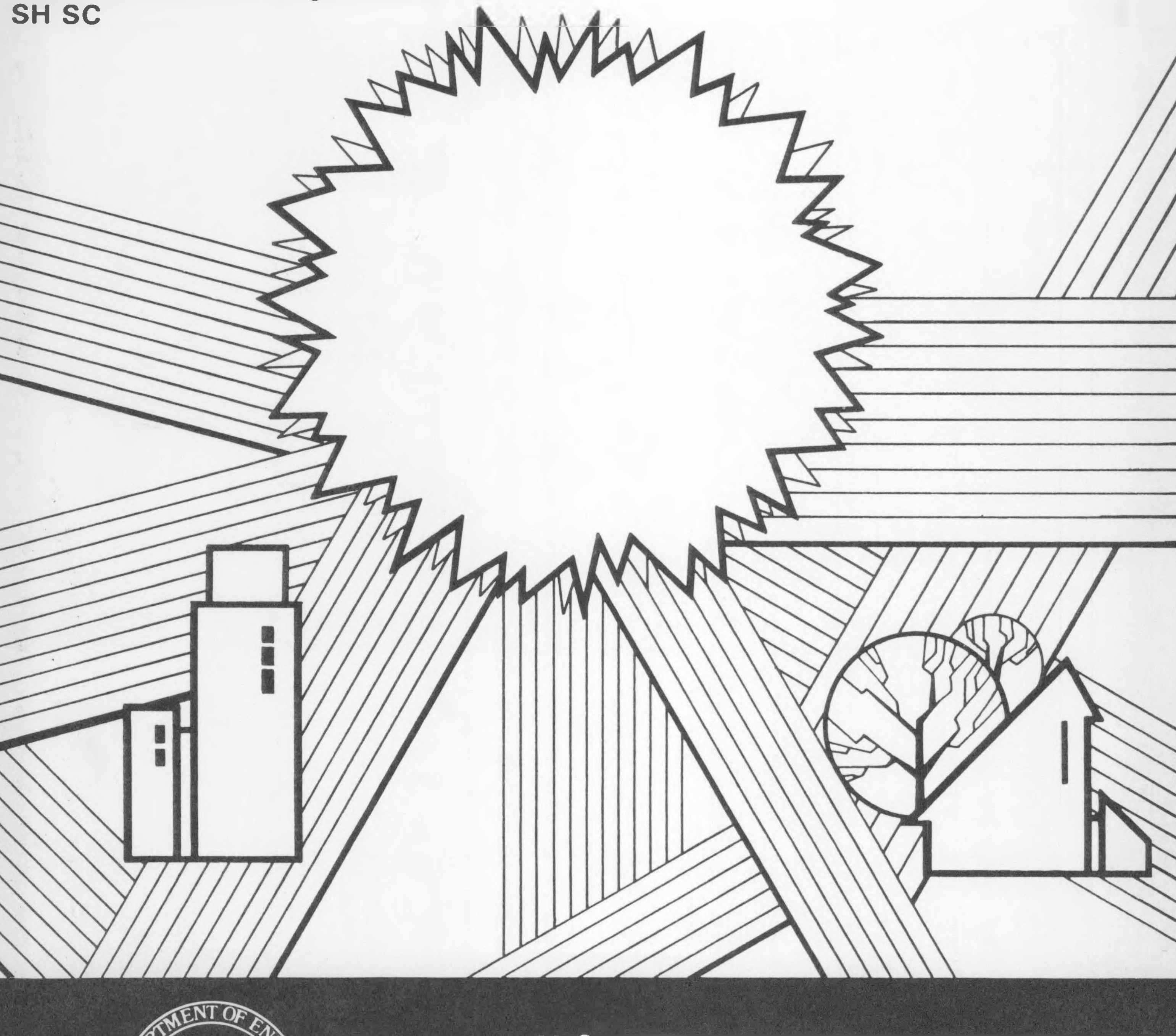

U.S. DEPARTMENT OF ENERGY

NATIONAL SOLAR DATA PROGRAM

SOLAR/2032-83/14
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UNIVERSITY OF MINNESOTA BOOKSTORE

MINNEAPOLIS, MINNESOTA

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

APRIL 1982 THROUGH AUGUST 1982

Prepared by T.L. Logee

Approved: [signature]
T.T. Bradshaw
Program Manager

Vitro Laboratories
14000 Georgia Avenue
Silver Spring, Maryland 20910

The National Solar Data Network
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9700 South Cass Avenue
Argonne, Illinois 60439

G.A. McGinnis, Project Manager

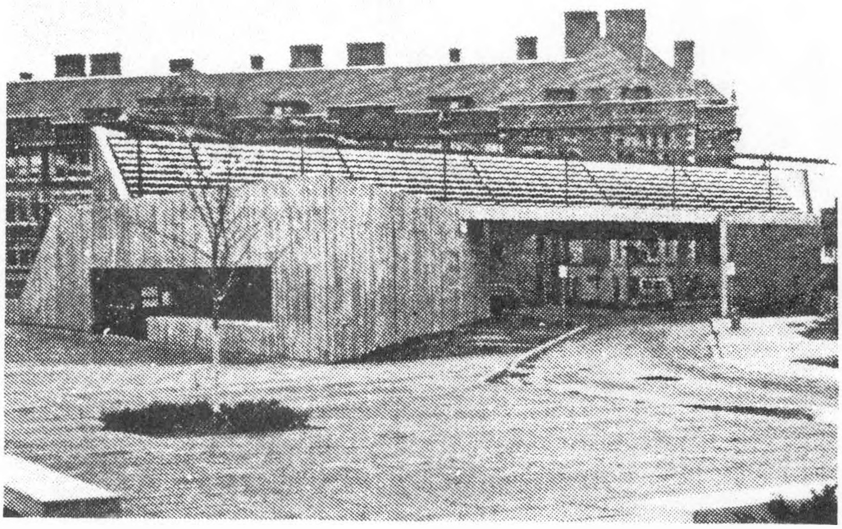
FOREWORD

This report is one of a series which describes the performance of solar energy systems in the National Solar Data Network (NSDN) for the heating and/or cooling seasons. Some NSDN installations are used solely for heating domestic hot water, and annual performance reports are issued for such sites. In addition, Monthly Performance Reports, prior to 1981, are available for the solar systems in the Network.

The National Solar Data Network consists of instrumented solar energy systems in buildings selected from among the 5,000 installations which are part of the National Solar Heating and Cooling Demonstration Program. Since 1981, some of the NSDN solar systems were also selected from the systems built by private industry without government funding. The overall purpose of this program is to assist in the development of solar technologies for buildings by providing data and information on the effectiveness of specific systems, the effectiveness of particular solar technologies, and the areas of potential improvement. Vitro Laboratories' responsibility in the NSDN, under contract with the Department of Energy, is to collect data daily from the sites, analyze the data, and disseminate information to interested users.

Buildings in the National Solar Data Network are residential, commercial, and institutional structures, geographically dispersed throughout the continental United States. The variety of solar systems installed employ "active" mechanical equipment systems or "passive" design features, or both, to supply solar energy to typical building thermal loads such as space heating, space cooling, and domestic hot water. Solar systems on some sites are used to supply commercial process heat.

The buildings in the NSDN program are instrumented to monitor thermal energy flows to the space conditioning, hot water, or process loads, from both the solar system and the auxiliary or backup system. Data collection from each site, and transmission to a central computer for processing and analysis, is highly automated.



UNIVERSITY OF MINNESOTA BOOKSTORE

UNIVERSITY OF MINNESOTA BOOKSTORE

The University of Minnesota Bookstore solar site (known as Williamson Hall) houses a bookstore and offices on the East Bank Campus of the University of Minnesota in Minneapolis, Minnesota. This active solar energy system is equipped with:

Collector:	Suntec concentrating Solar Linear Array Thermal System (SLATS), 6,350 square feet
Storage:	8,000 gallons in a buried tank
Auxiliary:	Central steam plant
Cooling:	Trane absorption chiller, 147 tons

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SECTION 1

SOLAR SYSTEM PERFORMANCE

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

Solar Fraction (SFR)[1]	5%
Solar Savings Ratio (SSR)[2]	0.02
Conventional Fuel Savings (TSVF, TSVE)[3]	9 tons of coal at the expense of 5,620 kwh of electrical energy
System Performance Factor (SYSPF)[4]	0.18
Solar System COP (COP)[5]	4.8

Seasonal Energy Requirements
April 1982 through August 1982
(Million BTU)

	Subsystem Load	Solar Contribution	% Solar
Heating	132	10.7	8
Cooling	693	28.7	4

Environmental Data

	Measured Average	Long-Term Average
Outdoor Temperature	67°F	62°F
Heating Degree-Days (Total)	480	965
Cooling Degree-Days (Total)	878	555
Daily Incident Solar Energy	1,553 BTU/ft^2	1,622 BTU/ft^2

1. $$\text{Solar Fraction} = \frac{\text{Solar Contribution to Loads [HSE + (CSE x TCECOP)]}}{\text{System Load (SYSL)}} \times 100$$

2. $$\text{Solar Savings Ratio} = \frac{\text{Solar Contribution to Loads [HSE + (CSE x TCECOP)] - Solar-Unique Operating Energy (CSOPE)}}{\text{System Load (SYSL)}}$$

3. Conventional Fuel Savings = Fossil Energy Savings in BTU x 0.05814 x 10^{-6} tons/BTU
   Electrical Expense in BTU x 292.8 x 10^{-6} kwh/BTU

4. $$\text{System Performance Factor} = \frac{\text{System Load (SYSL)}}{\text{Auxiliary Fossil Fuel (AXF) + 3.33 x System Operating Energy (SYSOPE)}}$$

5. $$\text{Solar System COP} = \frac{\text{Solar Energy Supplied to Loads (CSEO)}}{\text{Solar-Unique Operating Energy (CSOPE)}}$$

For definitions of acronyms in parentheses, refer to Appendix B.

1.1 SUMMARY AND CONCLUSIONS

The solar system at the University of Minnesota Bookstore provided a total of five percent of the combined space heating and cooling load of 825 million BTU. The solar savings ratio, which accounts for operating energy used to collect solar energy, was 0.02. Solar system performance was generally poor due to collector tracking and control problems. The performance of the system is shown in Table 1 and illustrated graphically in Figure 1.

Table 1. SOLAR SYSTEM THERMAL PERFORMANCE

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU, unless otherwise indicated)

MONTH	SOLAR ENERGY COLLECTED (SECA)	SYSTEM LOAD (SYSL)	SOLAR ENERGY USED (SEL)	AUXILIARY ENERGY FOSSIL (AXF)	SYSTEM OPERATING ENERGY (SYSOPE)	ENERGY SAVINGS FOSSIL (TSVF)	ENERGY SAVINGS ELECTRICAL (TSVE)	SOLAR FRACTION (%) (SFR)
APR	46.2	26.9	9.40	29.2	24.8	15.7	-5.97	30
MAY	18.2	110	7.13	256	69.5	11.9	-5.73	2
JUN	27.1	185	16.3	619	88.1	27.2	-3.44	3
JUL	42.3	297	36.6	1,370	122	61.0	-2.49	5
AUG	26.1	206	23.3	914	82.1	38.8	-1.52	4
TOTAL	160	825	92.7	3,188	387	154.6	-19.2	-
AVERAGE	32.0	165	18.5	638	77.3	30.9	-3.83	5

For a description of acronyms in parentheses, refer to Appendix B.

The fossil energy savings were 154.6 million BTU, equivalent to nine tons of coal, but there was an electrical energy expense of 19.2 million BTU (5,620 kwh). The system had a net energy savings of $49.09 based on energy costs of $41.36 per ton of coal and 5.75 cents per kwh.

Major energy flows to the heating and cooling subsystems are presented in Figure 2, the Energy Flow Diagram. This diagram shows where energy is collected, transported, used, and lost. In terms of solar energy utilization, the space cooling subsystem used 82 million BTU compared to 10.7 million BTU used in the space heating subsystem.

The active solar energy system was retrofitted in 1979 on a relatively new earth-sheltered building which houses a bookstore, admissions and records facility. The building is 95% below ground for energy conservation and to preserve open space on the campus.

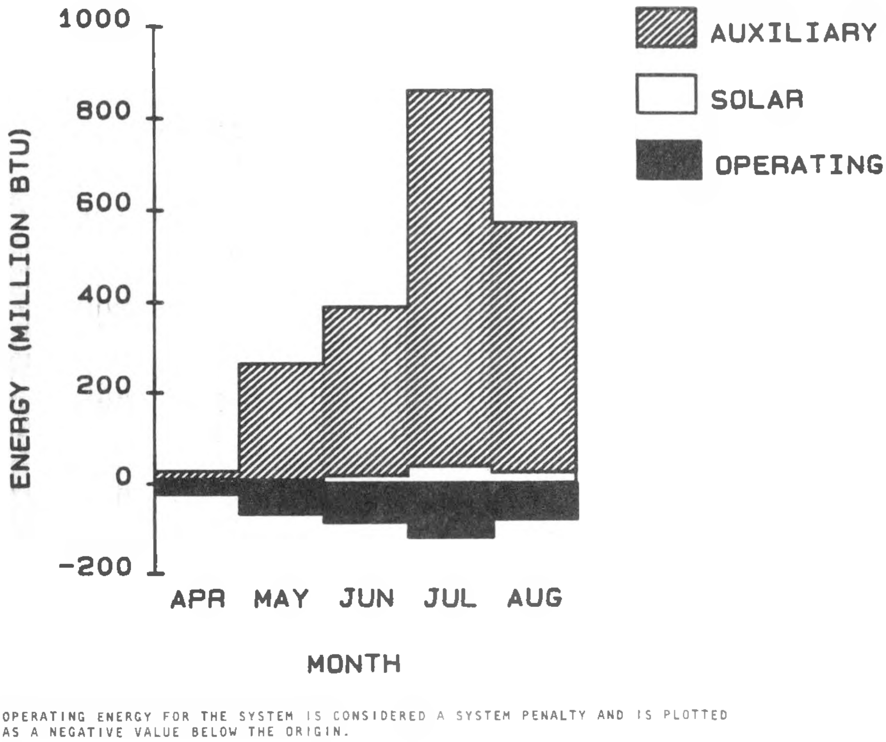

Figure 1. System Thermal Performance
University of Minnesota Bookstore
April 1982 through August 1982

Other energy conservation features are triple glazing on the windows, clerestories for daylighting and passive solar energy collection in winter, and a warm-air heat recovery system on the ventilation air. Due to the energy conservation features, the solar collection subsystem could be downsized and still provide large solar fractions.

The solar collector array is comprised of six stationary units of 10 movable reflectors, each about 110 feet long and one foot wide. These glass mirrors concentrate sunlight onto a copper absorber tube receiver.

Solar heated water from the storage tank or the collector array and water heated with auxiliary steam via a heat exchanger are delivered to a 147-ton absorption chiller for space cooling or to the heating coils for space heating.

The three major causes of poor system performance are the collector tracking controller, modulating control valves on the storage loop, and low absorption chiller Coefficient of Performance (COP). The control problem on the collector tracking controller resulted in

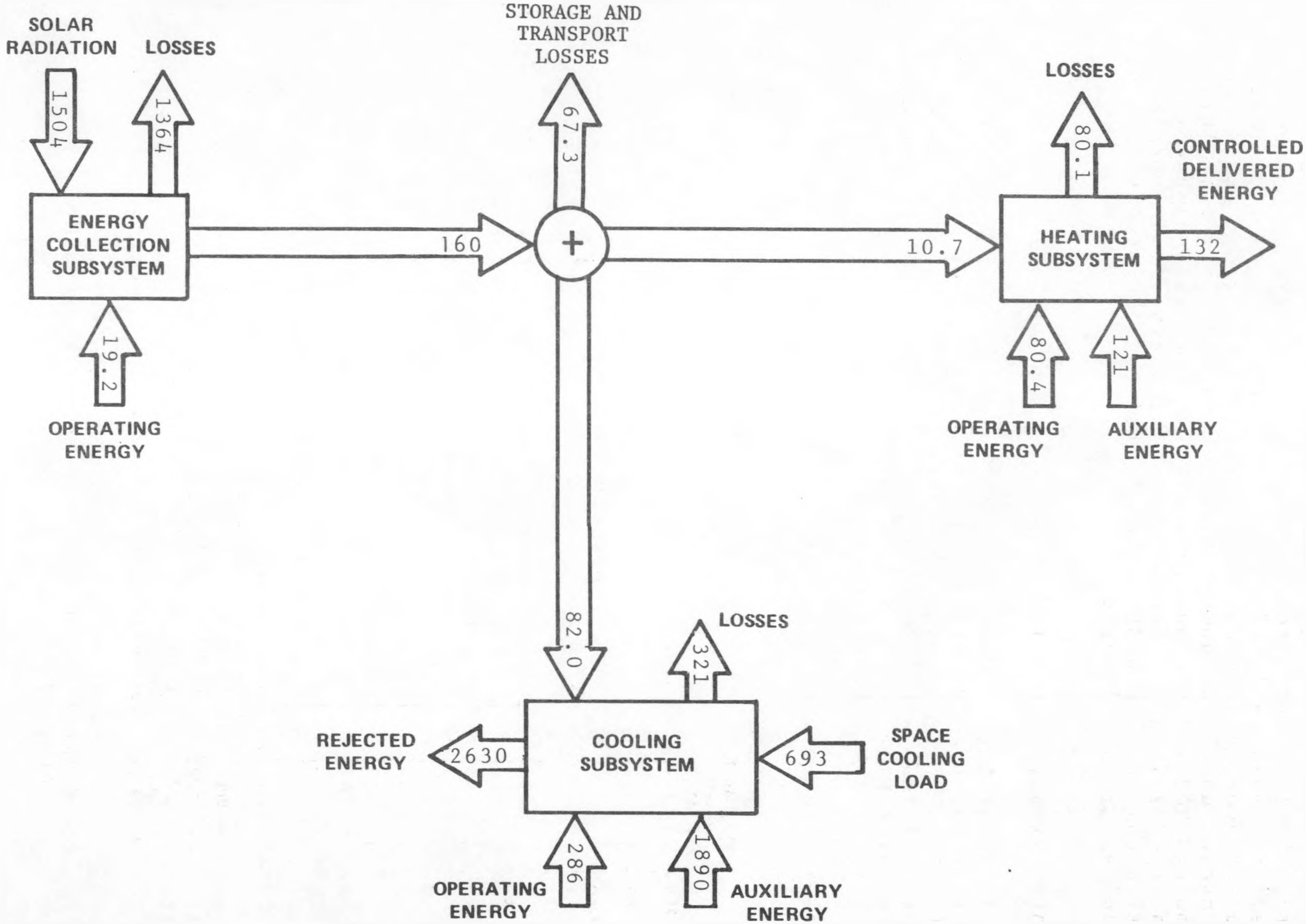

Figure 2. Energy Flow Diagram for the University of Minnesota Bookstore
April 1982 through August 1982
(Figures in million BTU)

very erratic output from the collector array. On some days, the collectors would remain stowed, would start in midafternoon, or just fail to track well. The modulating valves on the storage loop caused poor performance during part of the time because auxiliary heated water was pumped through the storage loop. This error maintained the storage tank at high temperatures and increased standby losses. Furthermore, the seasonal COP for the absorption chiller was 0.35, which is low. A COP of 0.55 can be achieved on a seasonal basis.

1.2 SOLAR ENERGY UTILIZATION

Figure 3, Solar Energy Use, shows the percentage of incident energy that was usable through each energy transfer process. The largest losses occurred at the collector array for the reasons mentioned previously. Effective use of the collected solar energy was also quite poor. Only 58% of the collected solar energy or six percent of the incident solar energy reached the desired subsystem. The transport and storage losses are partially due to the large piping network at this site.

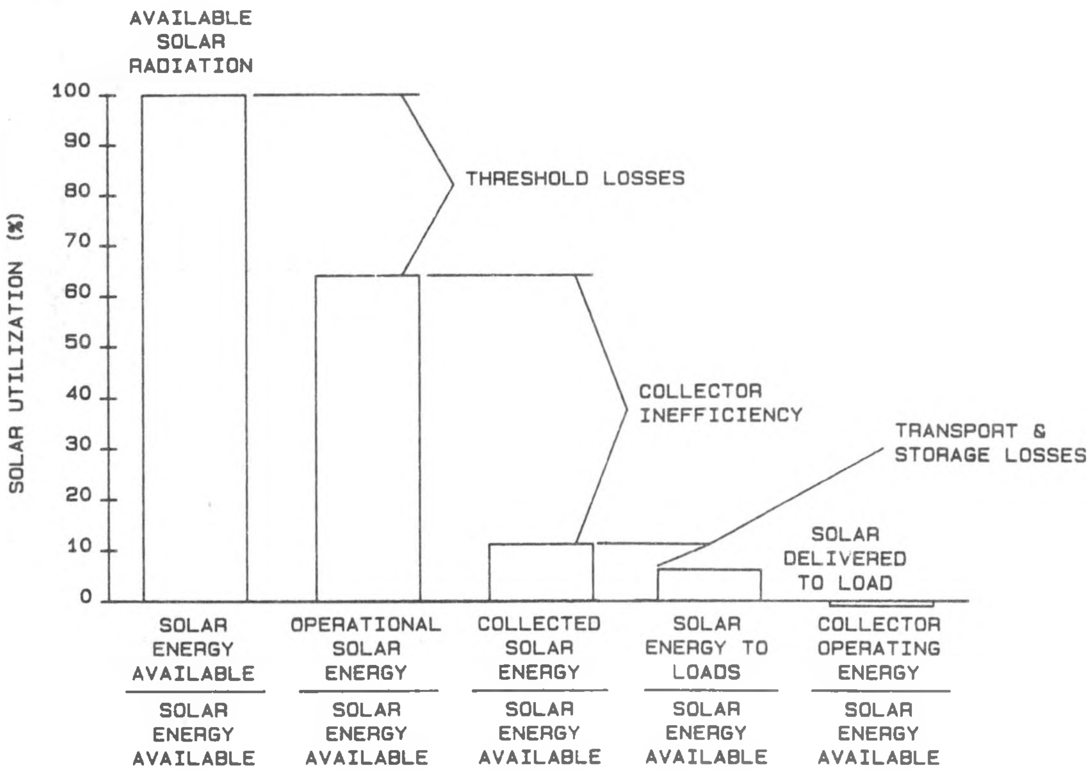

Figure 3. Solar Energy Use
University of Minnesota Bookstore
April 1982 through August 1982

SECTION 2

SUBSYSTEM PERFORMANCE

Detailed discussions of each major subsystem are presented in the sections which follow.

2.1 ENERGY COLLECTION SUBSYSTEM

The collector array performance is shown in Table 2.

The array collected 160 million BTU or 11% of the 1,504 million BTU incident. Collector operational efficiency was 17%. This poor performance was probably due to the winter storm damage (see Appendix A-3). The collector array efficiency and operational efficiency during the same period from 1981 was 29% and 46% respectively. These efficiencies are similar to those reported by Sandia Laboratories, Reference 10.

Table 2. COLLECTION SUBSYSTEM PERFORMANCE

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU, unless otherwise indicated)

MONTH	INCIDENT SOLAR RADIATION (SEA)	COLLECTED SOLAR ENERGY (SECA)	COLLECTOR SUBSYSTEM EFFICIENCY (%) (CLEF)	OPERATIONAL INCIDENT ENERGY (SEOP)	COLLECTOR ARRAY OPERATIONAL EFFICIENCY (%) (CLEFOP)	ECSS OPERATING ENERGY (CSOPE)	DAYTIME AMBIENT TEMPERATURE (°F) (TA)
APR	309	46.2	15	256	18	5.97	59
MAY	260	18.2	7	134	14	5.73	72
JUN	316	27.1	9	152	18	3.44	77
JUL	317	42.3	13	245	17	2.49	88
AUG	302	26.1	8	172	15	1.52	82
TOTAL	1,504	160	-	959	-	19.2	-
AVERAGE	300	32.0	11	192	17	3.83	76

For a description of acronyms in parentheses, refer to Appendix B.

Although Suntec personnel repaired and refocused the array in early April 1982, tracking was still erratic and unpredictable throughout the summer. There was also an attempt to repair the tracking controller, but no improvement was noted in collector efficiency.

The typical daily operation of the collector at the University of Minnesota Bookstore is shown in Figures 4 and 5.

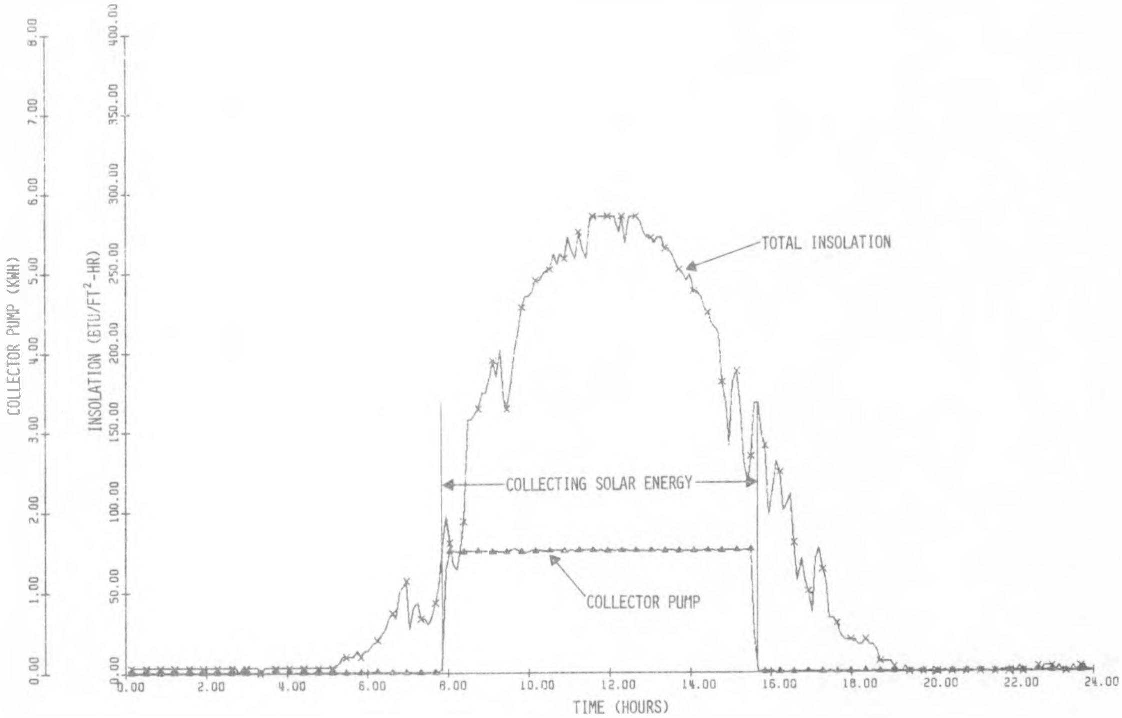

Figure 4. Typical Solar Insolation and
Collector Pump Operation
University of Minnesota Bookstore
August 2, 1982

To understand the typical operation of this solar system, the reader will require some more details about the control procedure. First, the collector pump is activated by a time clock. On Figure 4, this occurs at about 8:00 a.m. At this time, the solar insolation was 97 BTU/ft^2-hr, which was not enough to initiate tracking.

Note that neither the collector inlet nor outlet temperature changed much during the first hour of operation (see Figure 5). This was due to the fact that tracking had not been initiated. The tracking motor was started at 9:17 a.m. after total insolation had reached 200 BTU/ft^2-hr. This level was much higher than the design level of 127 BTU/ft^2-hr.

Once tracking had been initiated, the collector array still did not deliver any energy until the storage pump started at 10:15 a.m. (see Figure 5). The extra hour delay from the start of tracking until useful delivery of energy has several causes:

1. Poor functioning of the tracking controller.

2. The array size and long pipe runs (300 feet) have a large thermal mass which must be heated about 110^{o}F.

3. Useful energy delivery can only occur above 180°F, but the collector loop temperature must reach 195°F before the storage pump starts.

The solar collectors continued to track the sun until 3:25 p.m. The solar insolation at this time was less than 130 BTU/ft^2-hr. During peak collection in the early afternoon, the collectors maintained a 12°F temperature differential across the load heat exchanger. This good performance was at elevated collector temperatures (greater than 185°F) and with a temperature difference from the collector to ambient of greater than 85°F.

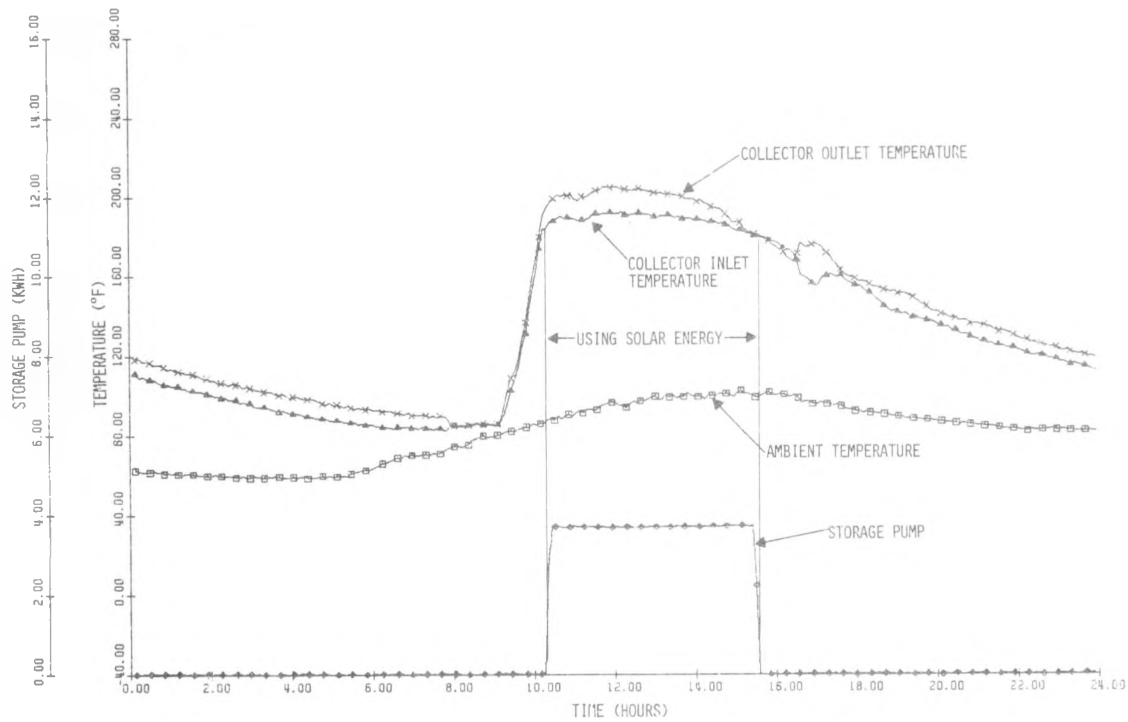

Figure 5. Typical Solar Collector Operation
University of Minnesota Bookstore
August 2, 1982

2.2 STORAGE SUBSYSTEM

The performance of the storage subsystem could not be analyzed because valves V-B and V-C modulate or vary the flow to the storage tank. Without a flow meter in either the supply or return from the storage tank, the energy flows into and out of the storage tank were unknown.

There is ample evidence from the data on storage tank temperatures that energy from the auxiliary boilers was used to maintain storage temperatures. This is not desirable because standby losses are increased. Also, this mode of operation was not a designed control mode.

2.3 SPACE HEATING SUBSYSTEM

The performance of the space heating subsystem is presented in Tables 3 and 3a. The solar energy system supplied 10.7 million BTU or eight percent of the 132 million BTU load. Note that April, with 394 heating degree-days, has a lower heating load than May or June. There was a control problem during May and June which caused the auxiliary system to cycle between heating and cooling. The control malfunction caused a greatly inflated space heating load during May and June.

The heating load divided by the heating degree-days is a useful number for comparing different months in the same building. In April 1982, this value was 68,300 BTU/heating degree-day, and 60,700 BTU/heating degree-day in April 1981. The same value for May 1982 was 634,000 BTU/heating degree-day, and 4.07 million BTU/heating degree-day in June 1982.

An estimate of the actual heating loads for May and June 1982 can be made by multiplying the April 1982 building load per heating degree-day by the heating degree-days in May or June. For May and June, the estimated building heating loads were 4.64 million BTU and 1.02 million BTU, respectively. The total building heating load would then have been 32.6 million BTU.

There were an estimated unnecessary 99.4 million BTU used for space heating. This excessive space heating equals 9.6 tons of coal at an 60% boiler efficiency. There was obviously an increased load on the air conditioning system too. The extra air conditioning load will be covered in Section 2.4.

Table 3. SPACE HEATING SUBSYSTEM

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU, unless otherwise indicated)

MONTH	SPACE HEATING LOAD (EHL)	TOTAL SOLAR ENERGY USED (HSE)	TOTAL AUXILIARY THERMAL USED (HAT)	SOLAR FRACTION OF LOAD (%) (HSFR)	BUILDING TEMPERATURE (°F) (TB)	AMBIENT TEMPERATURE (°F) (TA)
APR	26.9	9.40	17.5	30	73	52
MAY	43.1	0.85	42.2	2	77	65
JUN	61.0	0.46	60.5	1	78	68
JUL	0.0	0.00	0.0	0	77	78
AUG	0.81	0.00	0.81	0	78	74
TOTAL	132	10.7	121	-	-	-
AVERAGE	26.4	2.14	24.2	8	77	67

For a description of acronyms in parentheses, refer to Appendix B.

Table 3a. SPACE HEATING SUBSYSTEM (Continued)

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU, unless otherwise indicated)

MONTH	SPACE HEATING LOAD (EHL)	MEASURED SOLAR ENERGY USED (HSEM)	TOTAL OPERATING ENERGY (HOPE)	AUXILIARY FOSSIL FUEL (HAF)	HEATING DEGREE-DAYS (#) (HDD)
APR	26.9	9.40	18.8	29.2	394
MAY	43.1	0.85	26.5	70.4	68
JUN	61.0	0.46	34.8	100.9	15
JUL	0.0	0.00	0.0	0.0	0
AUG	0.81	0.00	0.34	1.35	3
TOTAL	132	10.7	80.4	202	480
AVERAGE	26.4	2.14	16.1	40.4	96

For a description of acronyms in parentheses, refer to Appendix B.

2.4 SPACE COOLING SUBSYSTEM

The performance of the space cooling subsystem is shown in Table 4.

Table 4. SPACE COOLING SUBSYSTEM

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU, unless otherwise indicated)

MONTH	COOLING LOAD (CL)	SOLAR FRACTION OF LOAD (%) (CSFR)	SOLAR ENERGY USED (CSE)	OPERATING ENERGY (COPE)	AUXILIARY THERMAL USED (CAT)	AUXILIARY FOSSIL FUEL (CAF)	BUILDING TEMPERATURE (°F) (TB)
APR	0.0	0	0.0	0.0	0	0	73
MAY	67.3	2	6.27	37.3	214	357	77
JUN	124	5	15.8	49.9	311	518	78
JUL	297	5	36.6	119	822	1,370	77
AUG	205	4	23.3	80.2	547	912	78
TOTAL	693	-	82.0	286	1,894	3,157	-
AVERAGE	139	4	16.4	57.2	378	632	77

For a description of acronyms in parentheses, refer to Appendix B.

Solar energy supplied four percent of the 693 million BTU cooling load. Note that the 82.0 million BTU of solar energy used does not directly supply the load as in space heating. There is a thermodynamic conversion process between the solar heated water and the cooling load that has an average COP of 0.35 in this instance, see Table 5. Therefore, 82.0 million BTU of solar energy provided a net of 28.7 million BTU of cooling.

Table 5. THERMODYNAMIC CONVERSION EQUIPMENT

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU, unless otherwise indicated)

MONTH	EQUIPMENT LOAD (TCEL)	THERMAL ENERGY INPUT (TCEI)	OPERATING ENERGY (TCEOPE)	ENERGY REJECTED (TCERJE)	COEFFICIENT OF PERFORMANCE (TCECOP)
APR	0.0	0	0.0	0	0.00
MAY	67.3	220	21.0	311	0.29
JUN	124	327	27.8	487	0.38
JUL	297	859	77.3	1,160	0.34
AUG	205	571	49.2	669	0.35
TOTAL	693	1,977	175	2,627	-
AVERAGE	139	396	35	526	0.35*

* Weighted average = $\Sigma(TCEL_{month})/\Sigma(TCEI_{month})$

For a description of acronyms in parentheses, refer to Appendix B.

Typical daily operation of the space cooling subsystem is shown in Figure 6. On this day in August, there was a continuous load on the absorption chiller. By 10:15 a.m., the solar collector loop had reached a temperature of 195°F, the startup set point on the storage pump. The sudden rise in the outlet temperature of the storage loop (labeled Solar Hot Water Supply Temperature) shows the effect of the storage pump startup. Note that the outlet temperature of the storage loop hovered above 190°F until about 1:30 p.m.

Interestingly, all of the collector output energy was utilized by the chiller. This usage is an example of a very good control system. The storage pump shut down at about 3:30 p.m. when the temperature at the storage loop outlet was nearly 180°F. There was nearly a 10°F temperature drop through the absorption chiller during the midday period (the difference between curves labeled Chiller Generator Inlet Temperature and Chiller Generator Outlet Temperature).

Note that the auxiliary boiler increased the solar energy temperature by 2°F to 5°F to maintain a chiller inlet temperature above

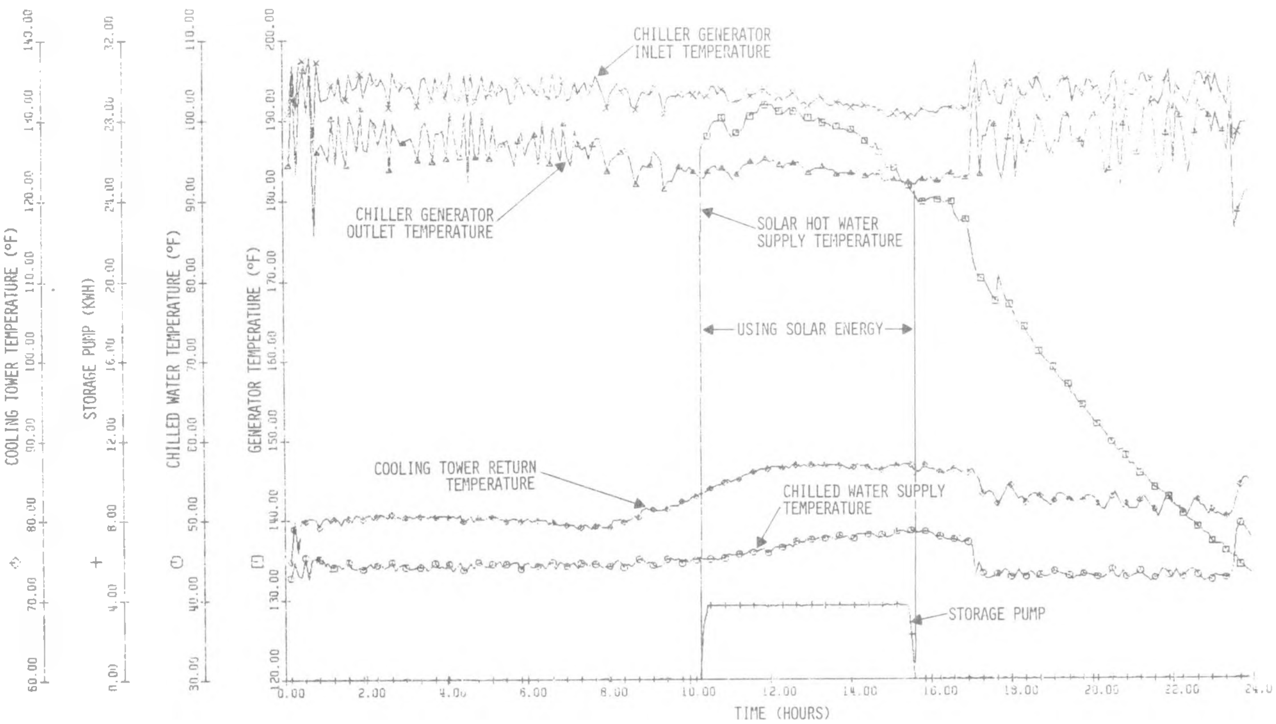

Figure 6. Typical Absorption Chiller Operation
University of Minnesota Bookstore
August 2, 1982

190°F. The chilled water outlet temperature ranged from 45°F to 48°F as the midday loads became greater. The cooling tower return temperature was maintained at about 80°F until the midday cooling loads raised it to 87°F. These chiller temperatures, generator inlet, chilled water outlet, and cooling tower return, were within the proper operating range for good absorption chiller operation.

In attempting to estimate the excess cooling caused by the cycling between cooling and heating in May and June, a similar index of building load per cooling degree-day can be used. The cooling load per cooling degree-day was 710,000 BTU/cooling degree-day for July 1982 and 700,000 BTU/cooling degree-day for August 1982. Using an average of 705,000 BTU/cooling degree-day results in an estimated cooling load of 42.3 million BTU in May and 74.0 million BTU in June. Therefore, the excess cooling load was 25 million BTU in May and 50 million BTU in June. The total extra cooling load was 75 million BTU compared to the extra 99.4 million BTU heating load. The difference between the two estimates could be due to some building overheating and measurement error. The extra coal required for cooling was much greater than 75 million BTU because of inefficiencies in the energy conversion process. The equivalent number of BTU used for space cooling was 357 million BTU or 20.8 tons of coal. The total energy cost of the malfunctioning building control was 30.4 tons of coal.

There were some improvements in utilization of solar energy during this cooling season. Although solar energy collection was much poorer this year (see Section 2.1), solar energy utilization during the cooling season was much higher. Solar energy utilization expressed as a percentage of solar energy collected increased from 23% in April 1982 to 89% in August 1982. This improvement in solar energy utilization was not attributable to valving storage out of the collection loop. Apparently maintaining the storage tank at or near 180°F was the reason for the improvement in solar energy utilization.

The thermodynamic conversion Coefficient of Performance (COP) of 0.35, mentioned earlier in this section, is the seasonal COP of the absorption chiller. This machine performed more poorly this year. In 1981, the seasonal COP was 0.48. This degradation of efficiency cost an estimated extra 540 million BTU, or 39 tons of coal.

SECTION 3

OPERATING ENERGY, ENERGY SAVINGS, AND WEATHER CONDITIONS

3.1 OPERATING ENERGY

From April 1982 through August 1982, the solar collection and storage subsystem used 19.2 million BTU or 5,620 kwh, see Table 6. There was no operating energy charged to the solar systems from the load subsystems because all of the equipment in these subsystems is necessary for the auxiliary subsystem.

Table 6. SOLAR OPERATING ENERGY

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU)

Month	ECSS (CSOPE)	SCS (COPE1)	TOTAL SOLAR (SYSOPE1)
APR	5.97	0.00	5.97
MAY	5.73	0.00	5.73
JUN	3.44	0.00	3.44
JUL	2.49	0.00	2.49
AUG	1.52	0.00	1.52
TOTAL	19.2	0.00	19.2
AVERAGE	3.83	0.00	3.83

For a description of acronyms in parentheses, refer to Appendix B.

The solar Coefficient of Performance (COP) is shown in Table 7. Note that there were much higher COPs in July and August. The COP is a ratio of the amount of energy collected or used to the energy required to collect it. The system COP is larger in July and August because of much higher solar utilization. The higher COP on the collection subsystem in July and August was probably due to resetting of the pump timer control.

Table 7. SOLAR COEFFICIENT OF PERFORMANCE

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

MONTH	SOLAR ENERGY SYSTEM	COLLECTION SUBSYSTEM
	(SEL / SYSOPE1)	(SECA / CSOPE)
APR	1.6	7.7
MAY	1.2	3.2
JUN	4.7	7.9
JUL	15	17
AUG	15	17
WEIGHTED AVERAGE	4.8	8.3

For a description of acronyms in parentheses, refer to Appendix B.

3.2 ENERGY SAVINGS

The energy savings are shown in Table 8. Net fossil energy savings were 154.6 million BTU at an electrical expense of 19.2 million BTU. This was a dollar savings of $49.09 for the period. Costs were computed at $41.36 per ton for coal and 5.75 cents per kwh for electricity. Delivered energy efficiency is assumed to be 60%.

Table 8. ENERGY SAVINGS

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

(All values in million BTU)

MONTH	SOLAR ENERGY USED (SEL)	SPACE HEATING FOSSIL FUEL (HSVF)	SPACE COOLING FOSSIL FUEL (CSVF)	ECSS OPERATING ENERGY SOLAR-UNIQUE (CSOPE)	NET ENERGY SAVINGS ELECTRICAL (TSVE)	NET ENERGY SAVINGS FOSSIL FUEL (TSVF)
APR	9.40	15.7	0.0	-5.97	-5.97	15.7
MAY	7.13	1.42	10.5	-5.73	-5.73	11.9
JUN	16.3	0.77	26.4	-3.44	-3.44	27.2
JUL	36.6	0.00	61.0	-2.49	-2.49	61.0
AUG	23.3	0.00	38.8	-1.52	-1.52	38.8
TOTAL	92.7	17.9	137	-19.2	-19.2	154.6
AVERAGE	18.5	3.58	27.4	-3.83	-3.83	30.9

For a description of acronyms in parentheses, refer to Appendix B.

3.3 WEATHER CONDITIONS

Average monthly weather conditions are shown in Table 9. For the period shown, the measured insolation of 1,553 BTU/ft^2-day is slightly less than the long-term insolation. Note that the measured insolation in April 1982 was eight percent higher than the long-term insolation. This month was an unusually sunny month over most of the United States.

Comparing the ambient temperatures, note that the period was eight percent warmer than the long-term average. The warmer season was also reflected in significantly less heating degree-days and more cooling degree days. Interestingly, ambient temperatures from the same period in 1981 were also much warmer, although there were not as many cooling degree-days in 1981.

Long-term data for the entire year is given in Appendix D.

Table 9. WEATHER CONDITIONS

UNIVERSITY OF MINNESOTA BOOKSTORE
APRIL 1982 THROUGH AUGUST 1982

MONTH	DAILY INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/FT^2-DAY)		AMBIENT TEMPERATURE (^{o}F)		HEATING DEGREE-DAYS		COOLING DEGREE-DAYS	
	MEASURED (SE)	LONG-TERM AVERAGE	MEASURED (TA)	LONG-TERM AVERAGE	MEASURED (HDD)	LONG-TERM AVERAGE	MEASURED (CDD)	LONG-TERM AVERAGE
APR	1,624	1,507	52	45	394	597	2	0
MAY	1,321	1,573	65	57	68	271	60	26
JUN	1,659	1,641	68	67	15	65	105	122
JUL	1,624	1,722	78	72	0	11	418	225
AUG	1,536	1,666	74	70	3	21	293	182
TOTAL	-	-	-	-	480	965	878	555
AVERAGE	1,553	1,622	67	62	96	193	176	111

For a description of acronyms in parentheses, refer to Appendix B.

SECTION 4

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6. Monthly Performance Report, University of Minnesota Bookstore, April 1982, Vitro Laboratories, Silver Spring, Maryland.

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8. Monthly Performance Report, University of Minnesota Bookstore, June 1982, Vitro Laboratories, Silver Spring, Maryland.

9. Monthly Performance Report, University of Minnesota Bookstore, July 1982, Vitro Laboratories, Silver Spring, Maryland.

10. Zender, S.N., Sandia Solar Total Energy Test Facility Project Final Report, Suntec 260 Square Meter SLATS Subsystem, SER 1022-60, Suntec Systems, Inc., Lakeville, Minnesota, November 1977.

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

APPENDIX A

SYSTEM DESCRIPTION

A-1 SYSTEM DESCRIPTION

A-2 MANUFACTURERS' DATA AND SYSTEM SPECIFICATIONS

A-3 SITE HISTORY AND PROBLEMS

APPENDIX A-1

SYSTEM DESCRIPTION

The University of Minnesota site in Minneapolis, Minnesota is an 84,000-square-foot underground building, housing a bookstore and other university-related facilities. The building is 95% below ground with its lowest floor 45 feet below the surface. The building was constructed underground to conserve 60% of the energy normally required by a building of this size. Natural light is admitted to the building through terraced south and west windows.

The solar energy system retrofitted to this building was designed to provide 63% of its heating needs and 40% of its cooling needs. Solar energy collection is accomplished using a concentrating collector array. The array, which consists of six stationary units mounted in a row on the surface over the building, faces 15 degrees east of south. Each of the six units consists of 10 individual, movable reflectors (each 110-feet-long by one-foot-wide) mounted along a 45 degree slope, and a fixed receiver supported over them. The 10 movable reflectors within each stationary unit track the sun by pivoting in north-south arcs around their long axes, in a coordinated motion. The reflectors focus sunlight on a stationary receiver at a concentration ratio of 35 to one. A water/glycol solution absorbs heat as it circulates through the copper absorber tubes in the receivers. The total effective collecting area is 6,350 square feet. Solar energy storage is provided by a buried 21-foot-long, eight-foot-diameter, insulated steel tank with an 8,000-gallon capacity.

The system provides both heating and cooling of the building's conditioned space. Cooling is accomplished using solar energy to power an absorption-cycle chiller. Auxiliary energy for both heating and cooling is provided by a central steam system which is fueled by coal. Interface with the conditioned air takes place at three large fan-coil units.

The concentrating collectors, which operate on the direct component of the total insolation, are set to track the sun when they receive 127 BTU/ft^2-hr (400 W/M^2) total insolation, and according to a timer. Pump P11 is energized by a timer with a seasonally dependent set point.

The system, shown schematically in Figure A-1, can be set in either its winter (space heating) or summer (space cooling) configuration. There are three modes of operation each for the space heating and space cooling configurations.

WINTER SPACE HEATING OPERATION

Mode 1 - Collector-to-Storage - When the incident solar energy is sufficient to raise the collector outlet temperature to 135°F and there is no space heating demand, this mode is activated. Pumps P11 and P12 are energized. Collected solar energy is delivered directly into the storage tank.

Mode 2 - Collector-to-Space Heating, Excess-to-Storage - This mode activates when incident solar energy is sufficient to raise the collector outlet temperature to 135°F and there is a space heating demand. Pumps P11 and P12 are energized to collect solar energy, and the load pump turns on. Heated water is delivered from the collector loop heat exchanger, past the auxiliary steam heating unit, to the three fan-coil units for space heating. If the temperature of the water leaving the coils is higher than the temperature of the water in the center of the tank, then this excess heat is delivered to the storage tank.

Mode 3 - Storage-to-Space Heating - When no incident solar energy is available and there is a space heating demand, then, if the storage tank temperature is above 120°F, the storage-to-space heating mode activates. Pump P12 and the load pump energize. Heated water is pumped from storage, past the auxiliary steam heating unit, to the three fan-coil units for space heating.

SUMMER SPACE COOLING OPERATION

Mode 1 - Collector-to-Storage - When the incident solar energy is sufficient to raise the collector outlet temperature to 180°F and there is no space cooling demand, this mode is activated. Pumps P11 and P12 are energized. Collected solar energy is delivered directly into the storage tank.

Mode 2 - Collector-to-Chiller, Excess-to-Storage - This mode activates when the incident solar energy is sufficient to raise the collector outlet temperature to 180°F and there is a space cooling demand. Pumps P11 and P12 are energized to collect solar energy, and one of the two cooling load pumps turns on. Heated water is delivered from the collector loop heat exchanger, past the auxiliary steam heating unit, to the chiller. On its return through the storage loop, any excess heat is delivered to the storage tank, to maintain the tank at 185°F. (Returning water is delivered to storage in this manner only if it is hotter than the water in the center of the tank.) Cold water from the chiller output is pumped to the three fan-coil units for space cooling.

Mode 3 - Storage-to-Chiller - When no incident solar energy is available and there is a space cooling demand, then, if the storage tank is at least 185°F, the storage-to-chiller mode activates. Pump P12 and one of the two cooling load pumps energize. Heated water is pumped from storage, past the auxiliary steam heating unit, to the chiller. Cold water from the chiller output is pumped to the three fan-coil units for space cooling.

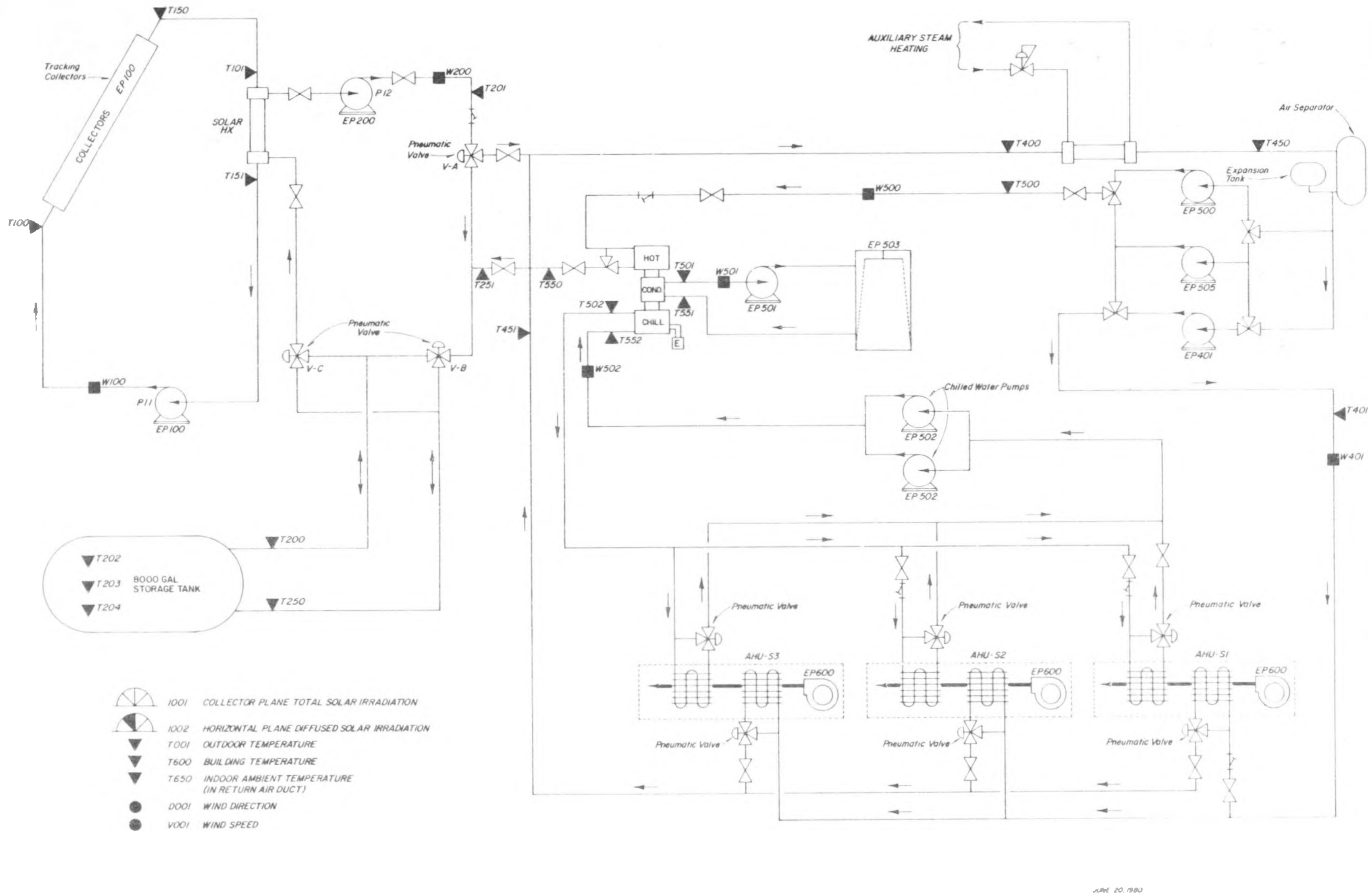


Figure A-1. University of Minnesota Bookstore Solar Energy System Schematic

APPENDIX A-2

MANUFACTURERS' DATA AND SYSTEM SPECIFICATIONS

The manufacturers of the major solar energy system components* include:

Collectors	Suntec concentrating SLATS	Suntec Systems, Inc.
Chiller	Model C2J-W-5 absorption chiller (147 tons)	Trane, Inc.
Storage	Eight-foot-diameter x 21-foot-long 8,000-gallon, steel, insulated tank	Wheeler Tank Manufacturing Co.

SYSTEM SPECIFICATIONS:

Focusing will occur when the incident insolation reaches 127 BTU/ft^2-hr. If the sun is obscured or dusk is approaching, the reflectors are rotated to the stowed position. However, there is a five-minute delay to prevent excessive rotation of the reflectors during partly cloudy days.

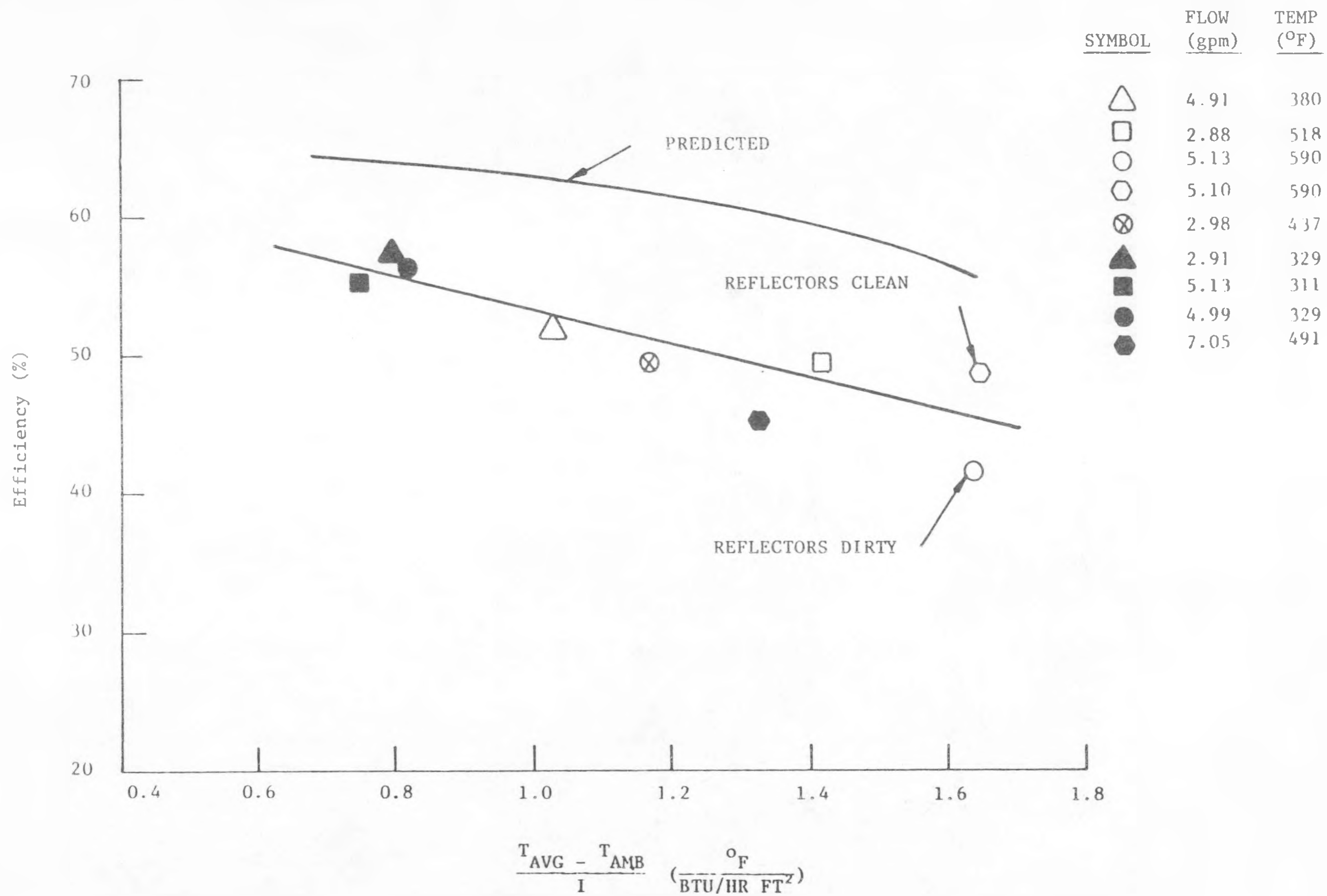
Freeze protection is provided by a 50% glycol solution.

Design loads:

Annual Energy Requirements (million BTU)

Application	Total Load	Solar Contribution	% Solar
Heating	860	542	63
Cooling	1,400	560	40

* See Figure A-2, Sandia test of new instantaneous efficiency.



From: Sandia Solar Total Energy Test Facility Project Final Report, Suntec 260 Square Meter SLATS Subsystem, SER 1022-60, Suntec Systems, Inc., Lakeville, Minnesota, November 1977.

Figure A-2. Noon Instantaneous Efficiency - Glass Reflectors

SECTION A-3

SITE HISTORY AND PROBLEMS

During a heavy snowstorm on December 2, 1981, seventeen of the 60 movable slats were damaged. Damage was so severe that the system was not operational until March 1982. In April 1982, representatives from the collector manufacturer, Suntec, spent considerable time focusing the collector slats. The remaining good mirrors were also consolidated to make completely functional subarrays. The area without mirrors was valved off until new mirrors could be installed.

During May and June 1982, solar tracking was very poor. This was attributed to weak batteries in the tracking control system. On several days with very good insolation, the solar collectors did not even operate. There was also a malfunction of the building Heating, Ventilation, and Air Conditioning (HVAC) controller during May and June. This problem resulted in the HVAC system cycling between cooling and heating. Consequently, these loads were higher than normal.

In July 1982, the storage tank was valved off to prevent auxiliary energy from maintaining storage temperatures. The storage tank remained valved off until mid-August, but the problem of auxiliary energy maintaining storage temperatures was not solved. The grantee is continuing to investigate the cause of this anomaly.

The erratic collector operation did not improve during July or August 1982. The tracking controller was still malfunctioning.

APPENDIX B

PERFORMANCE FACTORS AND SOLAR TERMS

APPENDIX B

PERFORMANCE FACTORS AND SOLAR TERMS

The performance factors identified in the site equations (Appendix C) by the use of acronyms or symbols are defined in this appendix. Section 1 describes general acronyms used in this report. Section 2 includes the acronym, the actual name of the performance factor, and a short definition.

Section 3 contains a glossary of solar terminology, in alphabetical order. These terms are included for quick reference by the reader.

Section 1. General Acronyms

Section 2. Performance Factor Definitions and Acronyms

Section 3. Solar Terminology

SECTION 1

GENERAL ACRONYMS

ATCE	Auxiliary Thermodynamic Conversion Equipment.
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineering.
BTU	British Thermal Unit, a measure of heat energy. The quantity of heat required to raise the temperature of one pound of pure water one degree Fahrenheit. One BTU is equivalent to 2.928×10^{-4} kwh of electrical energy.
COP	Coefficient of Performance. The ratio of total load to solar-source energy.
DHW	Domestic Hot Water.
ECSS	Energy Collection and Storage System.
HWS	Domestic or Service Hot Water Subsystem.
KWH	Kilowatt Hours, a measure of electrical energy. The product of kilowatts of electrical power applied to a load times the hours it is applied. One kwh is equivalent to 3,413 BTU of heat energy.
NSDN	National Solar Data Network.
SCS	Space Cooling Subsystem.
SHS	Space Heating Subsystem.
SOLMET	Solar Radiation/Meteorology Data.
TCE	Thermodynamic Conversion Equipment.

SECTION 2

PERFORMANCE FACTOR DEFINITIONS AND ACRONYMS

ACRONYM	NAME	DEFINITION
ASTECH	Change in Energy Stored in Cold Storage	Change in stored energy in cold storage during specific time period.
ASTEFF	Cold Storage Efficiency	Ratio of the sum of energy supplied to cold storage and the change in cold storage energy to the energy removed from cold storage.
ASTEI	Energy Delivered to Cold Storage	Amount of energy delivered to cold storage from the load.
ASTEO	Energy from Cold Storage	Amount of energy removed from cold storage by the chiller
ASTLOSS	Cold Storage Loss	Total energy losses from the cold storage subsystem.
ATCECOP	Auxiliary Cooling Subsystem Coefficient of Performance	The ratio of the auxiliary cooling subsystem load to thermal or electrical energy input.
ATCEI	Auxiliary Cooling Subsystem Thermal Energy Input	Equivalent thermal energy supplied as a fuel source to the auxiliary thermodynamic conversion equipment.
ATCEL	Auxiliary Cooling Load	Thermal energy removed from the air being cooled by the auxiliary thermodynamic conversion equipment.
ATCEOPE	Auxiliary Thermodynamic Conversion Equipment Operating Energy	Energy required to support the operation of the auxiliary thermodynamic conversion equipment; e.g., pumps, fans, etc.

ACRONYM	NAME	DEFINITION
ATCERJE	Auxiliary Rejected Energy	Amount of energy intentionally rejected from thermodynamic conversion equipment as a by-product of its operation.
ATST	Average Cold Storage Temperature	Average temperature of the cold storage medium.
AXE	Auxiliary Electric Fuel Energy to Load Subsystem	Amount of electrical energy required as a fuel source for all load subsystems.
AXF	Auxiliary Fossil Fuel Energy to Load Subsystem	Amount of fossil energy required as a fuel source for all load subsystems.
* AXT	Auxiliary Thermal Energy to Load Subsystems	Thermal energy delivered to all load subsystems to support a portion of the subsystem loads, from all auxiliary sources.
* BL	Building Load	Sum of heat conducted through the building walls and ceilings, and heat convected through cracks, doors, and windows as air infiltration.
CAE	SCS Auxiliary Electrical Fuel Energy	Amount of electrical energy provided to the SCS to be converted and applied to the SCS load.
CAF	SCS Auxiliary Fossil Fuel Energy	Amount of fossil energy provided to the SCS to be converted and applied to the SCS load.
CAREF	Collector Array Efficiency	Ratio of the collected solar energy to the incident solar energy.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
CAT	SCS Auxiliary Thermal Energy	Amount of thermal energy supplied to the SCS by the auxiliary equipment. For vapor compression units, it is CAE multiplied by compressor efficiency.
CDD	Cooling Degree-Days	A rough measure of the cooling requirement. This performance factor is the difference between the mean daily temperature, TAVE, and 65°F. If the mean is 65°F or less, cooling degree-days are zero.
CDE	Controlled Delivered Energy	Space heating intentionally delivered by the space heating subsystem including solar and auxiliary. This does not include heat losses from electric motors, pipes, storage, and other equipment.
* CL	Space Cooling Subsystem Load	Energy required to satisfy the temperature control demands of the space cooling subsystem.
CLAREA	Collector Array Area	The gross area of one collector panel multiplied by the number of panels in the array.
CLEF	Collection Subsystem Efficiency	Ratio of the energy collected to the total energy incident on the collector array.
CLEFOP	Operational Collection Subsystem Efficiency	Efficiency when there is fluid in the collector loop.
CLS	Solar Energy Contribution to Cooling Load	The portion of the total cooling load which was satisfied by solar energy.

* Primary Performance Factor

ACRONYM	NAME	DEFINITION
COPE	SCS Operating Energy	Amount of electrical energy required to support the SCS operation (fans and pumps) which is not intended to directly affect the thermal state of the subsystem.
COPE1	Solar-Specific Operating Energy	The operating energy necessary to the functioning of the solar energy portions of the SCS.
CSAUX	Auxiliary Energy to ECSS	Amount of auxiliary energy supplied to the ECSS.
* CSCEF	ECSS Solar Conversion Efficiency	Ratio of the solar energy supplied from the ECSS to the load subsystems to the incident solar energy on the collector array.
CSE	Solar Energy to SCS	Amount of solar energy delivered to the SCS.
CSEO	Energy Delivered from ECSS to Load Subsystems	Amount of energy supplied from the ECSS to the load subsystems (including any auxiliary energy supplied to the ECSS).
* CSFR	SCS Solar Fraction	Percentage of the SCS load which is supported by solar energy.
CSOPE	ECSS Operating Energy	Amount of energy used to support the ECSS operation (e.g., fans, pumps, etc.) which is not intended to affect directly the thermal state of the subsystem.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
CSRJE	ECSS Rejected Energy	Amount of energy intentionally rejected or dumped from the ECSS subsystem.
* CSVE	SCS Electrical Energy Savings	Difference in the electrical energy required to support an assumed similar conventional SCS and the actual electrical energy required to support the demonstration SCS, for identical SCS loads.
* CSVF	SCS Fossil Energy Savings	Difference in the fossil energy required to support an assumed similar conventional SCS and the actual fossil energy required to support the demonstration SCS, for identical SCS loads.
EHL	Equipment Heating Load	Amount of energy supplied to the space heating subsystem equipment: solar, auxiliary thermal, operating energy converted to heat, and losses from the space heating equipment which contribute to heating (the building heating load less internal gains).
GENOPE	Power Generation Operating Energy	The electrical energy required to operate the ECSS and Rankine subsystems when they are in the power generation mode.
HAE	SHS Auxiliary Electrical Fuel Energy	Amount of electrical energy provided to the SHS to be converted and applied to the SHS load.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
HAF	SHS Auxiliary Fossil Fuel Energy	Amount of fossil energy provided to the SHS to be converted and applied to the SHS load.
HAT	SHS Auxiliary Thermal Energy	Amount of thermal energy provided to the SHS by the auxiliary SHS.
HDD	Heating Degree-Days	A rough measure of the heating requirement. This performance factor is the difference between the mean daily temperature and 65°F. The mean is the average of the minimum and maximum temperatures for a given day. If the mean is 65°F or more, heating degree-days are zero.
HOPE	SHS Operating Energy	Amount of energy required to support the SHS operation (which is not intended to be applied directly to the SHS load).
HOPEI	Solar-Specific SHS Operating Energy	Operating energy necessary to the functioning of the solar energy portions of the SHS.
HOURCT	Record Time	Count of hours elapsed from the start of 1977.
HSE	Solar Energy to SHS	Amount of solar energy delivered to the SHS, including thermal losses from solar heated fluids.
HSEL	Solar Energy Losses to Load	Solar energy losses from storage and other equipment which heat the conditioned space.
HSEM	Measured Solar Energy to SHS	Solar energy intentionally delivered to SHS by the distribution network. Does not include solar energy losses which also sometimes contribute to space heating.

ACRONYM	NAME	DEFINITION
* HSFR	SHS Solar Fraction	Percentage of the SHS load which is supported by solar energy.
* HSVE	SHS Electrical Energy Savings	Difference in the electrical energy required to support an assumed similar conventional SHS and the actual electrical energy required to support the demonstration SHS, for identical SHS loads.
* HSVF	SHS Fossil Energy Savings	Difference in the fossil energy required to support an assumed similar conventional SHS and the actual fossil energy required to support the demonstration SHS, for identical SHS loads.
HWAE	HWS Auxiliary Electrical Fuel Energy	Amount of electrical energy provided to the HWS to be converted and applied to the HWS load.
HWAF	HWS Auxiliary Fossil Fuel Energy	Amount of fossil energy provided to the HWS to be converted and applied to the HWS load.
HWAT	HWS Auxiliary Thermal Energy	Amount of energy provided to the HWS by a heat transfer fluid from an auxiliary source.
HWCSM	Service Hot Water Consumption	Amount of heated water delivered to the load from the HWS.
HWCSMA	Tempered Hot Water Consumed	Total energy required to raise the hot water used from the supply water temperature to the hot water temperature.
HWDSFR	HWS Solar Fraction of Demand	Percentage of the "hot water demand" which is supplied by solar energy.
* HWL	Hot Water Subsystem Load	Amount of energy supplied to the HWS.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
HWOPE	HWS Operating Energy	Amount of energy required to support the HWS operation which is not intended to be applied directly to the HWS load.
HWOPEI	Solar-Unique HWS Operating Energy	"Operating energy" necessary to the functioning of the solar energy portions of the HWS.
HWSE	Solar Energy to HWS	Amount of solar energy delivered to the HWS.
HWSEI	Solar Energy to Preheat Tank	The amount of solar energy input to a preheat tank.
* HWSFR	HWS Solar Fraction	Percentage of the HWS load which is supported by solar energy.
* HWSVE	HWS Electrical Energy Savings	Difference in the electrical energy required to support an assumed similar conventional HWS and the actual electrical energy required to support the demonstration HWS, for identical HWS loads.
* HWSVF	HWS Fossil Energy Savings	Difference in the fossil energy required to support an assumed similar conventional HWS and the actual fossil energy required to support the demonstration HWS, for identical loads.
LINLOS	Recirculation Loop Losses	Thermal energy losses due to recirculation of hot water in a large building loop.
OUTVC	Cooling Produced	Space cooling provided by the air conditioner; energy removed from the conditioned space.
PARA	Rankine Parasitic Power	Amount of auxiliary electrical energy supplied per unit time to the refrigerant pump and the Rankine subsystem controls.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
PRELOS	Preheat Tank Losses	The difference between the input solar energy to a preheat tank and the output solar energy to the HWS tank. This includes losses and changes in internal energy.
PWRGEN	Rankine Power Generated	Amount of electrical energy per unit time produced by the motor generator from the shaft power of the gas turbine.
PWRSVE	Rankine Power Generation Savings	The net output of the Rankine engines when operating in the power generation mode.
RANKOUT	Rankine Turbine Output	Mechanical energy developed at the output shaft of the Rankine engine gas turbine. Includes energy losses in the gearbox. This shaft output can drive a motor generator or an air conditioning compressor.
REFF	Rankine Thermal Efficiency	The ratio of RANKOUT to RSE. This percentage was developed from laboratory experimental data taken from gas turbines operating under typical conditions at the solar sites.
RELH	Relative Humidity	Average outdoor relative humidity at the site.
ROPE	Rankine Operating Energy	Amount of electrical energy required to support the Rankine system. Includes energy for boiler feedwater pumping, cooling tower pumping, cooling tower fan and parasitics.
RSCAE	Rankine Auxiliary Electric Used	Amount of auxiliary electrical energy supplied to the motor generator for driving the air conditioning compressor.

ACRONYM	NAME	DEFINITION
RSCOP	Rankine Coefficient of Performance	The ratio of useful energy provided by the Rankine subsystem including the associated air conditioner to the operating and auxiliary energy input to the subsystem. Specifically, it is (OUTVC + PWRGEN)/(RSCAE + ROPE).
RSE	Rankine Solar Energy Used	Amount of solar energy supplied to boil the refrigerant which drives the Rankine cycle gas turbine.
RSRJE	Rankine Energy Rejected	Amounts of energy intentionally rejected through the cooling tower from the Rankine condenser and air conditioning condenser.
* SE	Incident Solar Energy	Amount of solar energy incident upon one square foot of the collector plane.
SEA	Incident Solar Energy on Array	Amount of solar energy incident upon the collector array.
* SEC	Collector Solar Energy	Amount of thermal energy added to the heat transfer fluid for each square foot of the collector area.
* SECA	Collected Solar Energy by Array	Amount of thermal energy added to the heat transfer fluid by the collector array.
SEDF	Diffuse Insolation	Amount of diffuse solar energy incident upon one square foot of a collector plane.
* SEL	Solar energy to Load Subsystems	Amount of solar energy supplied by the ECSS to all load subsystems.
SEOP	Operational Incident Solar Energy	Amount of solar energy incident upon the collector array when the collector loop is active.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
* SFR	Solar Fraction of System Load	Percentage of the system load which was supported by solar energy.
SSSR	System Solar Savings Ratio	The ratio of the sum of the solar contributions to the system load minus the solar-specific system operating energy to the total system load.
STECH	Change in ECSS Stored Energy	Change in ECSS stored energy during specific time period.
STEFF	ECSS Storage Efficiency	Ratio of the sum of energy supplied by ECSS storage and the change in ECSS stored energy to the energy delivered to the ECSS storage.
STEI	Energy Delivered to ECSS Storage	Amount of energy delivered to ECSS storage by the collector array and from auxiliary sources.
STEO	Energy Supplied by ECSS Storage	Amount of energy supplied by ECSS storage to the load subsystems.
STLOSS	Storage Loss	Total energy losses from the storage subsystem.
STOCAP	Storage Capacity	The volumetric storage capacity of the storage subsystem.
STPER	Effective Heat Transfer Coefficient	The overall heat transfer coefficient for the hot solar storage tank as measured for the month: ratio of storage loss to product of outside tank area, temperature difference across insulation, and number of hours in the month.
SYSCOP	System Coefficient of Performance	The ratio of the total solar energy delivered to the load to the sum of the solar operating energies.
* SYSL	System Load	Energy required to satisfy all desired temperature control demands at the output of all subsystems.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
* SYSOPE	System Operating Energy	Amount of energy required to support the system operation, including all subsystems, which is not intended to be applied directly to the system load.
SYSOPE1	Solar System Operating Energy	Operating energy that is specifically used for the solar components of the system.
* SYSPF	System Performance Factor	Ratio of the system load to the total equivalent fossil energy expended or required to support the system load.
* TA	Ambient Temperature	Average temperature of the ambient air.
TANKV	HWS Heat-up Energy	The energy required to heat all the water in the HWS tank from the cold water supply temperature to the hot water outlet temperature.
TAVE	Average Daily Temperature	The average daily temperature as defined by the National Weather Service; i.e., the average of the minimum and maximum temperatures for a given day.
* TB	Building Temperature	Average temperature of the air in the controlled space of the building.
TCECOP	TCE Coefficient of Performance	Coefficient of performance of the thermodynamic conversion equipment, typically, the ratio of equipment load to thermal energy input.
TCEI	TCE Thermal Input Energy	Equivalent thermal energy which is supplied as a fuel source to thermodynamic conversion equipment.
TCEL	Thermodynamic Conversion Equipment Load	Controlled energy output of thermodynamic conversion equipment.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
TCEOPE	TCE Operating Energy	Amount of energy required to support the operation of thermodynamic conversion equipment (e.g., pumps and fans).
TCERJE	TCE Reject Energy	Amount of energy intentionally rejected or dumped from thermodynamic conversion equipment as a by-product or consequence of its principal operation.
TDA	Daytime Average Ambient Temperature	Average temperature of the ambient air during the daytime (during normal collector operation period).
* TECSM	Total Energy Consumed by System	Amount of energy demand of the system from external sources; sum of all fuels, operating energies, and collected solar energy.
THW	Service Hot Water Temperature	Average temperature of the service hot water supplied by the system.
TRANKC	Rankine Condensing Water Temperature	Temperature of the heat transfer fluid at the inlet to the condenser of the gas turbine subsystem.
TRANKS	Rankine Solar Water Temperature	Temperature of the heat transfer fluid at the inlet to the refrigerant boiler of the gas turbine.
TST	ECSS Storage Temperature	Average temperature of the ECSS storage medium.
* TSVE	Total Electrical Energy Savings	Difference in the estimated electrical energy required to support an assumed similar conventional system and the actual electrical energy required to support the system, for identical loads; sum of electrical energy savings for all subsystems.

* Primary Performance Factors

ACRONYM	NAME	DEFINITION
* TSVF	Total Fossil Energy Savings	Difference in the estimated fossil energy required to support an assumed similar conventional system and the actual fossil energy required to support the system, for identical loads; sum of fossil energy savings of all subsystems.
TSW	Supply Water Temperature	Average temperature of the supply water to the hot water subsystem.
WDIR	Wind Direction	Average wind direction at the site.
WIND	Wind Velocity	Average wind velocity at the site.

* Primary Performance Factor

SECTION 3

SOLAR TERMINOLOGY

Absorptivity	The ratio of radiation absorbed by a surface to the total radiated energy incident on that surface.
Active Solar System	A system in which a transfer fluid (liquid or air) is circulated (by pump or fan) through a solar collector.
Air Conditioning	Popularly defined as space cooling; more precisely, the process of treating indoor air by controlling the temperature, humidity, and distribution to maintain specified comfort conditions.
Ambient Temperature	The surrounding air temperature.
Array	An assembly of a number of collector elements, or panels, into the solar collector for a solar energy system.
Auxiliary Energy	In solar energy terminology, the energy supplied to the heating or cooling load from other than the solar source, usually from a conventional heating or cooling system. Excluded are operating energy, and energy which may be supplemental in nature but does not have the auxiliary system as an origin; e.g., energy supplied to the space heating load from the external environment by a heat pump.
Auxiliary Energy Subsystem	In solar energy terminology, the auxiliary energy system is the conventional heating and/or cooling equipment used as a supplement or backup to the solar system.
Backflow	Reverse flow.
Backflow Preventer	A valve or damper installed in a pipe or duct to prevent reverse flow of the fluid.
Beam Radiation	Radiated energy received directly, not from scattering or reflecting sources.

Collected Solar Energy	The thermal energy added to the heat transfer fluid by the solar collector.
Collection Subsystem	The assembly of components that absorbs incident solar energy and transfers the absorbed thermal energy to a heat transfer fluid.
Collector Array Efficiency	Same as Collector Conversion Efficiency. Ratio of the collected solar energy to the incident solar energy. (See also Operational Collector Efficiency.)
Collector Conversion Efficiency	Ratio of thermal energy output to solar energy incident on the collector array.
Concentrating Solar Collector	A solar collector that concentrates the energy from a larger area onto an absorbing element of smaller area.
Conditioned Space	The space in a building in which the air is heated or cooled to maintain a desired temperature range.
Control System or Subsystem	The assembly of electric, pneumatic, or hydraulic, sensing, and actuating devices used to control the operating equipment in a system.
Cooling Degree-Days	The sum over a specified period of time of the number of degrees the mean daily temperature is above $65^{o}F$.
Cooling Tower	A heat exchanger that transfers waste heat to outside ambient air.
Diffuse Radiation	Solar radiation which is scattered by air molecules, dust, or water droplets and incapable of being focused.
Drainback	Automatic draining of the collector array and piping to storage each time the collector pump shuts off.
Draindown	A system equipped with automatic or manual valves which drain the solar collectors and collector piping to prevent freezing in the event of cold weather.

Duct Heating Coil	A liquid-to-air heat exchanger in the duct distribution system.
Effective Heat Transfer Coefficient	The heat transfer coefficient, per unit plate area of a collector, which is a measure of the total heat losses per unit area from all sides, top, back, and edges.
Energy Gain	The thermal energy gained by the collector transfer fluid. The thermal energy output of the collector.
Energy Savings	The estimated difference between the fossil and/or electrical energy requirements of an assumed conventional system (carrying the full measured load) and the actual electrical and/or fossil energy requirements of the installed solar-assisted system.
Expansion Tank	A tank with a confined volume of air (or gas) whose inlet port is open to the system heat transfer fluid. The pressure and volume of the confined air varies as the system heat transfer fluid expands and contracts to prevent excessive pressure from developing and causing damage.
F-Chart	A computer program developed by the University of Wisconsin Solar Energy Laboratory, which calculates solar heating system performance and economics.
Fixed Collector	A solar collector that is fixed in position and cannot be rotated to follow the sun daily or seasonably.
Flat-Plate Collector	A solar energy collecting device consisting of a relatively thin panel of absorbing material. A container with insulated bottom and sides and covered with one or more covers transparent to visible solar energy and relatively opaque to infrared energy. Visible energy from the sun enters through the transparent cover and raises the temperature of the absorbing panel. The infrared energy reradiated from the panel is trapped within the collector

Flat-Plate Collector (Continued)	because it cannot pass through the cover. Glass is an effective cover material (see Selective Surface).
Focusing Collector	A concentrating type collector using parabolic mirrors or optical lenses to focus the energy from a large area onto a small absorbing area.
Fossil Fuel	Petroleum, coal, and natural gas derived fuels.
Glazing	In solar energy terminology, the transparent covers used to reduce energy losses from a collector panel.
Heat Exchanger	A device used to transfer energy from one heat transfer fluid to another while maintaining physical segregation of the fluids. Normally used in systems to provide an interface between two different heat transfer fluids.
Heat Transfer Fluid	The fluid circulated through a heat source (solar collector) or heat exchanger that transports the thermal energy by virtue of its temperature.
Heating Degree-Days	The sum over a specified period of time of the number of degrees the mean daily temperature is <u>below</u> 65°F.
Incidence Angle	The angle between the line to a radiating source (the sun) and a line normal to the plane of the surface being irradiated.
Incident Solar Energy	The amount of solar energy irradiating a surface taking into account the angle of incidence. The effective area receiving energy is the product of the area of the surface times the cosine of the angle of incidence.
Insolation	Incoming solar radiation
Instantaneous Efficiency	The efficiency of a solar collector at one operating point, $\frac{Ti - Ta}{I}$, under steady-state conditions (see Operating Point).

Instantaneous Efficiency Curve	A plot of solar collector efficiency against operating point, $\frac{Ti - Ta}{I}$, (see Operating Point).
Load	That to which energy is supplied, such as space heating load or cooling load. The system load is the total solar and auxiliary energy required to satisfy the heating or cooling requirements.
Manifold	The piping that distributes the transport fluid to and from the individual panels of a collector array.
Microclimate	Highly localized weather features which may differ from long-term regional values due to the interaction of the local earth's surface with the atmosphere.
Nocturnal Radiation	The loss of thermal energy by the solar collector to the night sky.
Operating Energy	The amount of energy (usually electrical energy) required to operate the solar and auxiliary equipments and to transport the thermal energy to the point of use, and which is not intended to directly affect the thermal state of the system.
Operating Point	A solar energy system has a dynamic operating range due to changes in level of insolation (I), fluid input temperature (Ti), and outside ambient temperature (Ta). The operating point is defined as: $$\frac{Ti - Ta}{I} \left(\frac{^{o}F \times hr \times ft^2}{BTU}\right)$$
Operational Collector Efficiency	Ratio of collected solar energy to incident solar energy only during the time the collector fluid is being circulated with the intention of delivering solar-source energy to the system.
Outgassing	The emission of gas by materials and components, usually during exposure to elevated temperature, or reduced pressure.

Passive Solar System	A system which uses architectural components of the building to collect, distribute, and store solar energy.
Pebble Bed (Rock Bed)	A space filled with uniform-sized pebbles to store solar-source energy by raising the temperature of the pebbles.
Reflected Radiation	Insolation reflected from a surface, such as the ground or a reflecting element, onto the solar collector.
Rejected Energy	Energy intentionally rejected, dissipated, or dumped from the solar system.
Retrofit	The addition of a solar energy system to an existing structure.
Selective Surface	A surface that has the ability to readily absorb solar radiation, but reradiates little of it as thermal radiation.
Sensor	A device used to monitor a physical parameter of a system, such as temperature or flow rate, for the purpose of measurement or control.
Solar Conditioned Space	The area in a building that depends on solar energy to provide a fraction of the heating and cooling needs.
Solar Fraction	The fraction of the total load supplied by solar energy. The ratio of solar energy supplied to loads divided by total load. Often expressed as a percentage.
Solar Savings Ratio	The ratio of the solar energy supplied to the load minus the solar system operating energy, divided by the system load.
Storage Efficiency, η_s	Measure of effectiveness of transfer of energy through the storage subsystem taking into account system losses.
Storage Subsystem	The assembly of components used to store solar-source energy for use during periods of low insolation.

Stratification — A phenomenon that causes a distinct thermal gradient in a heat transfer fluid, in contrast to a thermally homogeneous fluid which results in the layering of the heat transfer fluid, with each layer at a different temperature. In solar energy systems, stratification can occur in liquid storage tanks or rock beds, and may even occur in pipes and ducts. The temperature gradient or layering may occur in a horizontal, vertical, or radial direction.

System Performance Factor — Ratio of system load to the total equivalent fossil energy expended or required to support the system load.

Ton of Refrigeration — The heat equivalent to the melting of one ton (2,000 pounds) of ice at 32°F in 24 hours. A ton of refrigeration will absorb 12,000 BTU/hr, or 288,000 BTU/day.

Tracking Collector — A solar collector that moves to point in the direction of the sun.

Zone — A portion of a conditioned space that is controlled to meet heating or cooling requirements separately from the other space or other zones.

APPENDIX C

DATA ACCURACY AND PERFORMANCE EQUATIONS

APPENDIX C

DATA ACCURACY AND PERFORMANCE EQUATIONS

UNIVERSITY OF MINNESOTA BOOKSTORE

INTRODUCTION

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

DATA ACCURACY ESTIMATES

The primary tool used to determine the data requirements and the selection of instrumentation is the analytical heat balance. Sufficient heat balance calculations are required to equate the total energy input to the total energy output for the subsystem or component under study to provide an energy balance closure of less than 10%. As a general rule, a six percent accuracy is assumed for NSDN performance results, based on the requirements described in Reference C-1 and other theoretical calculations and tests from Reference C-2.

Errors greater than approximately 10% for active systems and 15% for passive systems will not permit useful comparison between different systems. Error analysis of most performance evaluation factors for active NSDN solar energy systems has shown that the experimental data is obtained with accuracy of about ± six percent using the sensors shown in Table C-1. (Reference C-2)

The data accuracy conclusions were based on a composite of all available information sources, including:

- Field data from selected sample sites (Reference C-2)
- Manufacturers' accuracy data (Reference C-2)
- Internal laboratory calibration data (References C-2)
- Site verification from special accuracy tests (Reference C-2)
- Special tests required to verify system accuracy

Table C-1. SENSOR ACCURACY

THE NATIONAL SOLAR DATA NETWORK

PARAMETER	SENSOR TYPE	MANUFACTURER	ACCURACY (% of Full Scale unless indicated)
Temperature	3-wire Platinum Resistance Thermometer (RDT)	Minco	± 0.5°F
Insolation	Precision Spectral Pyranometer	Eppley	± 3% 0-70° Angle ± 6% 70-80° Angle
Wind	Propeller-type Anemometer	WeatherMeasure	± 1% <25 mph ± 3% >25 mph
Humidity	Solid State	WeatherMeasure	± 3% <80% RH ± 6% >80% RH
Liquid Flow (Rate)	Impact-type Target Flow Meter	Ramapo	± 1% ½" to 3½" Pipe ± 2% 4" Pipe
Liquid Flow (Total)	Nutating Disk Flow Meter	Hersey	± 1.5% Total Flow
Air Flow	Thermal Anemometer	Kurz	± 2% -68 - 140°F
Fuel Flow	Oscillating Piston Flow Meter	Kent	± 1% Full Scale
Gas Flow	Bellows Type-4 Chamber	American	± 1% Full Scale
Electric Power	Hall Effect Transducer	Ohio Semitronics	± 0.5% Full Scale
Heat Flux	Thermoelectric Junction	Hy-Cal Engineering	± 2% Linearity ± 0.5% Repeatability

The error elements of the NSDN data system are categorized into three major groups. These are the sensor error sources, the Site Data Acquisition Subsystem (SDAS) error sources, and the computational error sources. Each of these areas is briefly discussed below. Additional detail is available in Reference C-2.

Sensor errors are defined as all error sources arising between the point of measurement and the input to the SDAS. Sensor errors are of two types. The first type is inherent sensor error. These errors are independent of the installation of a sensor at a particular location. The sources for quantifying these errors are manufacturers' references and laboratory tests conducted at the manufacturers' facilities. Estimates of these errors are given in Table C-1.

The second type of sensor error is 'in-situ' or location error. These errors are specific to the sensor location, sensor wiring, installation technique, and to the state of the system where the measurement is made. In general, sensors for all sites have been installed in accordance with manufacturers' and National Bureau of Standards (NBS) standards, in order to minimize errors due to sensor location. (See Reference C-2.)

SDAS errors are defined as all errors propagated in the Site Data Acquisition Subsystem.

Two sources of SDAS accuracy data are available. An unpublished report details the results of testing performed at Argonne National Laboratory (ANL). Error numbers related to the variation of regulated voltages within the SDAS from several sources were established and found to be less than 0.05% in most cases. A significant area of concern was long-term drift of readings at many sites. Line voltage variation, temperature regime of the SDAS, and repair/replacement were found to have less significance. Secondly, side-by-side testing of a fully deployed sensor/SDAS system resulted in performance factor accuracy within $\pm$ six percent of reference measurement.

Computational errors are propagated from application of analytical techniques to the data stream, and include rounding errors, data gap errors and sampling rate errors.

Estimation of actual computational errors was accomplished using computer simulation to determine round-off and sampling rate errors, the effect of data gap bridging, and the effect of errors in the measurement of certain constants and auxiliary parameters that affect performance factor computations. The effects of these errors were established by actual measurement at the test sites, data acquired from other sources, and from analytical techniques. Results of these tests are available in Reference C-2. In general, the results showed no significant introduction of error in computations at most sites.

Data is occasionally lost at NSDN sites for a variety of reasons. Values for missing data elements are created by a data bridging routine. There will always be some error associated with the estimation process.

For data losses of 10% or less, the performance factor accuracy is not significantly affected. Most errors are less than three percent. All but one are four percent or less. The significant exception is change in stored energy, which is very sensitive to data loss.

Some performance factors are stable with relatively large data loss. Calculation of overall system performance generally remains stable with less than 20% data loss. (Reference C-2)

The results of several related studies indicate that the measurement of the performance of typical active solar systems can be accomplished with a relatively high degree of accuracy. Performance factor accuracy is within the National Bureau of Standards (NBS) criteria of six percent accuracy. (Reference C-1) Exceptions are those performance factors which depend directly on the estimation of burner efficiency or estimates due to known sensor failures.

PERFORMANCE FACTORS

Data samples from the system measurements are integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This 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 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

$$\text{SOLAR ENERGY AVAILABLE} = \Sigma\ [\text{I001} \times \text{CLAREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in BTU per square foot per hour, CLAREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval.

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

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

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

For a liquid system, ΔH is generally given by

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

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

For an air system, ΔH is generally given by

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

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

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

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = 3413 \; \Sigma \; [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the factor 3413 corrects the data to BTU/hour.

Letter Designations

C or CP	=	Specific Heat
D	=	Direction or Position
EE	=	Electric Energy
EP	=	Electric Power
F	=	Fuel Flow Rate
HWD	=	Functional procedure to calculate the enthalpy change of water at the average of the inlet and outlet temperatures
H	=	Enthalpy
HR	=	Humidity Ratio
I	=	Incident Solar Flux (Insolation)
M	=	Mass Flow Rate
N	=	Performance Parameter
P	=	Pressure
PD	=	Differential Pressure
Q	=	Thermal Energy
RHO	=	Density
T	=	Temperature
TD	=	Differential Temperature
TI	=	Time
V	=	Velocity
W	=	Heat Transport Medium Volume Flow Rate
_P	=	Appended to a function designator to signify the value of the function during the previous iteration

Subsystem Designations Number Sequence	Subsystem/Data Group
001 to 099	Climatological
100 to 199	Collector and Heat Transport
200 to 299	Thermal Storage
300 to 399	Hot Water
400 to 499	Space Heating
500 to 599	Space Cooling
600 to 699	Building/Load

EQUATIONS USED TO GENERATE MONTHLY PERFORMANCE VALUES

WEATHER DATA

AVERAGE AMBIENT TEMPERATURE (^{o}F)

TA = T001

AVERAGE BUILDING TEMPERATURE (^{o}F)

TB = T600

DAYTIME AVERAGE AMBIENT TEMPERATURE (^{o}F)

TDA = T001

for $\pm$ three hours from solar noon

BUILDING RELATIVE HUMIDITY (%)

RELH = RH600

WIND VELOCITY (MPH)

WIND = V001

WIND DIRECTION

WDIR = D001

unless WDIR <1.0

then WDIR = WDIR_P

COLLECTION SUBSYSTEM

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

SE = I001

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

SEDF = I002

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

SEOP = I001 x CLAREA

when the collector loop is activated

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

SECA = M100 x CPE38W x (T150 - T100)

where CPE38W refers to the specific heat of a 38% ethylene glycol/water solution.

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

SEA = CLAREA x SE

COLLECTED SOLAR ENERGY (BTU/FT^2)

SEC = SECA/CLAREA

COLLECTOR ARRAY EFFICIENCY

CLEF = SECA/SEA

COLLECTOR ARRAY OPERATIONAL EFFICIENCY

CLEFOP = SECA/SEOP

ECSS OPERATING ENERGY (BTU)

CSOPE = 56.8833 x (EP100 + EP101 + EP200)

STORAGE SUBSYSTEM

AVERAGE TEMPERATURE OF STORAGE (^{o}F)

TST = (T202 + T203 + T204)/3

SOLAR ENERGY TO STORAGE (BTU)

STEI = M200 x CP x (T200 - T250)

if D250 = 0

SOLAR ENERGY FROM STORAGE (BTU)

STEO = M200 x CP x (T200 - T250)

if D250 = 1

CHANGE IN STORED ENERGY (BTU)

STECH1 = STOCAP x CP(TST1) x RHO(TST1) x TST1

STECH = STECH1 - $STECH1_p$

where the subscript $_p$ refers to a prior reference value

TST1 = last hourly storage temperature

STORAGE LOSS (BTU)

STLOSS = STEI - STEO - STECH

AUXILIARY TO STORAGE (BTU)

AT = M401 x CP x (T451 - T400)

if M401 > 0 and T451 > T400

AT = M500 x CP x (T550 - T400)

if M500 > 0 and T550 > T400

TOTAL AUXILIARY IN STORAGE (BTU)

ATS = ATS + AT

TOTAL ENERGY TO STORAGE (BTU)

TTS = TTS + SECA + AT

AUXILIARY FROM STORAGE DURING HEATING (BTU)

AFSH = ATS/TTS x HSE

AUXILIARY FROM STORAGE DURING COOLING (BTU)

AFSC = ATS/TTS x CSE

STORAGE EFFICIENCY (%)

STEFF = (STECH + STEO)/STEI x 100

EFFECTIVE HEAT TRANSFER COEFFICIENT ($BTU/^{o}F-FT^{2}-HR$)

STPER = STLOSS/[SUR_AREA x (TST - AMB)]

SUR_AREA = storage tank surface area

AMB = temperature surrounding storage tank

SPACE HEATING SUBSYSTEM

SPACE HEATING SOLAR-UNIQUE OPERATING ENERGY (BTU)

HOPE1 = 0

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

HOPE = 56.8833 x Σ (EP401 + EP600)

in heating mode

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

HSE = M401 x CP x (T400 - T451) - AFSH

SPACE HEATING AUXILIARY THERMAL ENERGY (BTU)

HAT = M401 x CP x (T401 - T400) + AFSH

SPACE HEATING AUXILIARY FOSSIL ENERGY (BTU)

HAF = HAT x 0.6

where 0.6 is an assumed boiler efficiency

SPACE HEATING LOAD (BTU)

CDE = HSE + HAT

EHL = CDE

SPACE HEATING SOLAR FRACTION (%)

$$HSFR = 100 \times HSE/(HSE + HAT)$$

SPACE HEATING FOSSIL SAVINGS (BTU)

$$HSVF = HSE/0.6$$

where 0.6 is an assumed boiler efficiency

SPACE COOLING SUBSYSTEM

SPACE COOLING OPERATING ENERGY (BTU)

$$COPE = 56.8833 \times \Sigma\ (EP500 + EP501 + EP502 + EP503 + EP504 + EP505 + EP600)$$

SPACE COOLING - SOLAR-UNIQUE OPERATING ENERGY (BTU)

$$COPE1 = 0$$

SPACE COOLING AUXILIARY FOSSIL ENERGY (BTU)

$$CAF = CAT \times 0.6$$

where 0.6 is an assumed boiler efficiency

SPACE COOLING AUXILIARY THERMAL ENERGY (BTU)

$$CAT = M500 \times CP \times (T500 - T400) + AFSC$$

SOLAR ENERGY TO SPACE COOLING SUBSYSTEM (BTU)

$$CSE = M500 \times CP \times (T400 - T550) - AFSC$$

SPACE COOLING LOAD (BTU)

$$CL = M502 \times CP \times (T552 - T502)$$

SPACE COOLING SOLAR FRACTION (%)

$$CSFR = 100 \times CSE/(CSE + CAT)$$

SPACE COOLING FOSSIL SAVINGS (BTU)

$$CSVF = CSE/0.6$$

where 0.6 is an assumed boiler efficiency

SPACE COOLING ELECTRICAL SAVINGS (BTU)

$$CSVE = -COPE1$$

THERMODYNAMIC CONVERSION EQUIPMENT (SOLAR-UNIQUE CHILLER)

TCE EQUIPMENT LOAD (BTU)

TCEL = M502 x CP x (T552 - T502)

TCE INPUT ENERGY (BTU)

TCEI = M500 x CP x (T500 - T550)

TCE REJECTED ENERGY (BTU)

TCERJE = M501 x CP x (T501 - T551)

TCE OPERATING ENERGY (BTU)

TCEOPE = 56.8833 x (EP500 + EP501 + EP502 + EP503 + EP504 + EP505)

TCE CHILLER COP

TCECOP = TCEL/TCEI

SYSTEM FACTORS

ENERGY TO LOADS (BTU)

CSEO = CSE + HSE

SOLAR ENERGY USED (BTU)

SEL = CSEO

ECSS SOLAR CONVERSION EFFICIENCY (%)

CSCEF = SEL/SEA

SYSTEM LOAD (BTU)

SYSL = CL + EHL

SYSTEM SOLAR FRACTION (%)

SFR = (CSFR x CL + HSFR x EHL)/SYSL

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = CSOPE + COPE + HOPE

SYSTEM AUXILIARY FOSSIL ENERGY (BTU)

AXF = HAF + CAF

SYSTEM AUXILIARY THERMAL ENERGY (BTU)

AXT = HAT + CAT

SYSTEM ELECTRICAL SAVINGS (BTU)

TSVE = HSVE + CSVE - CSOPE

SYSTEM FOSSIL SAVINGS (BTU)

TSVF = HSVF + CSVF

TOTAL ENERGY CONSUMED (BTU)

TECSM = SECA + SYSOPE + AXF

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXF + 3.33 x SYSOPE)

SOLAR SAVINGS RATIO

SSSR = (HSE + CSE x CSFR - CSOPE - COPE1 - HOPE1)/SYSL

APPENDIX C

REFERENCES

C-1 Streed, E., et al. Thermal Requirements and Performance Evaluation Procedures for the National Heating and Cooling Demonstration Program, NBSIR 76-1137, National Bureau of Standards, Washington, D.C., 1976.

C-2 Seropian, A. Data Accuracy Study (Two Parts), Technical Memo #03200.8, Vitro Laboratories, Silver Spring, Maryland, March 13, 1981.

APPENDIX D

LONG-TERM WEATHER DATA

APPENDIX D

LONG-TERM WEATHER DATA

These long-term average weather data were obtained from nearby representative National Weather Service and SOLMET meteorological stations. The long-term insolation values are total global horizontal radiation values converted to collector angle and azimuth orientation (to represent insolation at tilted surfaces) by a TRNSYS-type radiation processor (see Footnote 1). Long-term temperatures were based on interpolation of historical temperature records of nearby weather stations.

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[1] Computation method given in "TRNSYS, a Transient Simulation Program," Engineering Experiment Station Report #38, Solar Energy Laboratory, University of Wisconsin, Madison.

UNIVERSITY OF MINNESOTA BOOKSTORE LONG-TERM WEATHER DATA

COLLECTOR TILT: 45 DEGREES
LATITUDE: 45.12 DEGREES

LOCATION: MINNEAPOLIS, MINNESOTA
COLLECTOR AZIMUTH: -5 DEGREES

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1052.	465.	0.44179	1.985	922.	1637	0	12.
FEB	1531.	763.	0.49853	1.647	1257.	1358	0	17.
MAR	2179.	1102.	0.50590	1.300	1434.	1138	0	28.
APR	2888.	1442.	0.49913	1.045	1507.	597	0	45.
MAY	3416.	1737.	0.50840	0.906	1573.	271	26	57.
JUN	3641.	1928.	0.52966	0.851	1641.	65	122	67.
JUL	3525.	1969.	0.55850	0.875	1722.	11	225	72.
AUG	3090.	1689.	0.54646	0.986	1666.	21	182	70.
SEP	2433.	1254.	0.51528	1.192	1494.	173	23	60.
OCT	1719.	859.	0.49972	1.517	1303.	472	7	50.
NOV	1163.	479.	0.41231	1.813	869.	978	0	32.
DEC	925.	354.	0.38260	2.002	709.	1438	0	19.

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.

APPENDIX E

ENERGY CONVERSION FACTORS

APPENDIX E

ENERGY CONVERSION FACTORS

Fuel Type	Energy Content	Fuel Source Conversion Factor
Coal	8,600 BTU/pound 17.2×10^6 BTU/ton	0.05814×10^{-6} tons/BTU
Electricity	3,413 BTU/kilowatt-hour	292.8×10^{-6} kwh/BTU
Kerosene	135,000 BTU/gallon	7.41×10^{-6} gallons/BTU
Natural gas	1,021 BTU/cubic foot	979.4×10^{-6} cubic feet/ BTU
Oil, distillate fuel[1]	138,690 BTU/gallon	7.21×10^{-6} gallons/BTU
Oil, residual fuel[2]	149,690 BTU/gallon	6.68×10^{-6} gallons/BTU
Propane	91,500 BTU/gallon	10.93×10^{-6} gallons/BTU

[1] No. 1 and No. 2 heating oils, diesel fuel, No. 4 fuel oils

[2] No. 5 and No. 6 fuel oils

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