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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

WASHINGTON NATURAL GAS
KIRKLAND, WASHINGTON
November 1979, February
and April 1980
DHW SH

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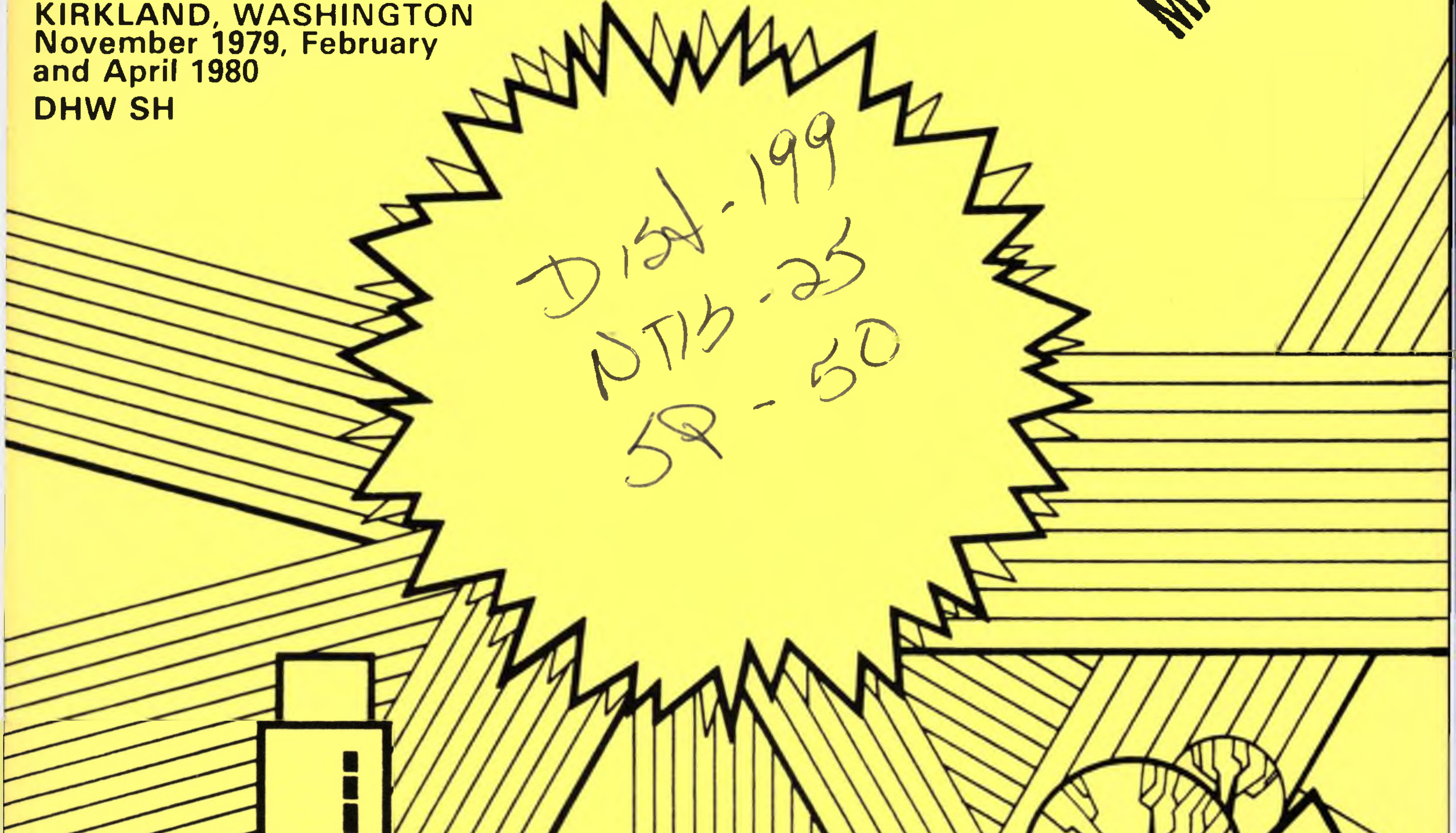

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NATIONAL SOLAR DATA PROGRAM

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WASHINGTON NATURAL GAS

KIRKLAND, WASHINGTON

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

NOVEMBER 1979, FEBRUARY AND APRIL 1980

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9700 South Cass Avenue
Argonne, Illinois 60439

A. A. Longnecker, Project Manager

FOREWORD

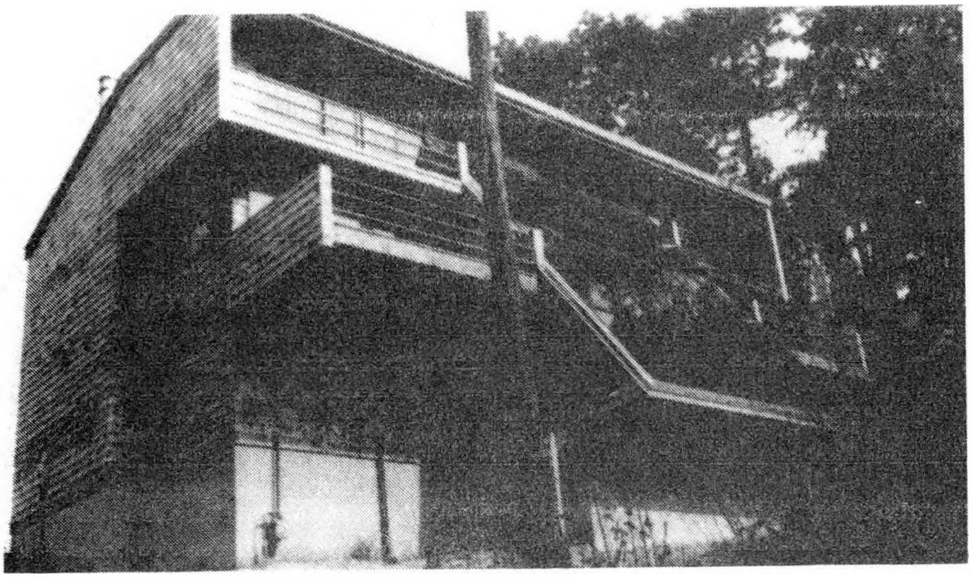
This report is one of a series which describes the performance of solar energy systems in the National Solar Data Network (NSDN) for the entire heating or cooling season. Domestic hot water is also included, if there is a solar contribution. Some NSDN installations are used solely for heating domestic hot water and annual performance reports are issued for such sites. In addition, Monthly Performance Reports 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 built (since early 1977) as part of the National Solar Heating and Cooling Demonstration Program. The overall purpose of this program is to reduce the use of nonrenewable fuels by encouraging the application of solar energy for heating, cooling, and domestic hot water. Vitro Laboratories Division operates the NSDN, under contract with the Department of Energy, to collect daily data from the sites, analyze the data, and disseminate information to interested users.

Buildings in the National Solar Data Network are comprised of residential, commercial and institutional structures which are geographically dispersed throughout the continental United States, Hawaii and Puerto Rico. 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.

In addition to these "Seasonal" Reports, NSDN information is disseminated for each operational site via Monthly Performance Reports, and special reports.



WASHINGTON NATURAL GAS

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WASHINGTON NATURAL GAS

The Washington Natural Gas solar energy site is a single family residence in Kirkland, Washington. The active solar energy system is designed to supply the following:

Seasonal Design Factors
November 1979, February, and April 1980
(Million BTU)

	Total Load	Solar Contribution	% Solar
Heating and Hot Water	31.4	13.0	41%

It is equipped with:

Collector	591 ft^2 (546 ft^2 net area) Solaron flat-plate air-medium collector array
Storage	Underground 273 ft^3 concrete and wood storage bin containing about 27,300 pounds of smooth stones, insulated
Auxiliary	Gas forced-air furnace for space heating Gas heater for domestic hot water

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SECTION 1

SOLAR SYSTEM PERFORMANCE

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

Solar Fraction[1]	22%
Solar Savings Ratio[2]	11%
Conventional Fuel Savings[3]	6,491 cubic feet of natural gas
Conventional Electrical Expense[3]	308 kwh
System Performance Factor[4]	0.54
Solar System COP[5]	7.67

Seasonal Energy Requirements
November 1979, February and April 1980
(million BTU)

	Total Load	Solar Contribution	% Solar
Heating	14.35	3.06	21
Hot Water	3.38	0.69	23

Environmental Data

	Measured Average	Long-Term Average
Outdoor temperature	47°F	45°F
Heating degree-days	539	579
Daily incident solar energy	806 BTU/ft^2	891 BTU/ft^2

1. $$\text{Solar Fraction} = \frac{\text{Solar Energy Supplied to Loads}}{\text{Total Load}}$$

2. $$\text{Solar Savings Ratio} = \frac{\text{Solar Energy Supplied to Load - Solar System Operating Energy}}{\text{Total Load}}$$

3. $$\text{Conventional Fuel Savings} = \frac{\text{Solar Energy Supplied to Loads}}{0.6}; \quad \text{Conventional Electric Expense} = (\text{Expense in BTUs}) \times 2.928 \times 10^{-4}\ \text{kwh/BTU}$$

4. Ratio of system load to the total equivalent fossil energy expended or required to support the system load.

5. $$\text{Solar System COP} = \frac{\text{Solar Energy Used}}{\text{Solar Unique Operating Energy Required for Collection}}$$

1.1 SUMMARY AND CONCLUSIONS

The Washington Natural Gas Company site is a single family residence in Kirkland, Washington. The home has approximately 2,607 square feet of conditioned space. Solar energy is used for space heating and for preheating domestic hot water (DHW). The solar energy system has a Solaron flat-plate collector array with a gross area of 591 square feet. The collector array, built into the side of the house, faces south at an angle of 57 degrees to the horizontal. Air is used as the medium for delivering solar energy from the collector array to storage and to space heating and hot water loads. Solar energy is stored undergound in a 273 cubic foot bin containing 27,300 pounds of smooth stones. The bin has one inch of fiberglass and two inches of styrofoam insulation. Preheated water is stored in an 80-gallon preheat storage tank, and supplied on demand to a conventional 50-gallon DHW tank. When solar energy is insufficient to satisfy the space heating load, a gas furnace provides auxiliary energy for space heating. Similarly, a gas-fired unit in the DHW tank provides auxiliary energy for water heating.

During the reported heating season of November 1979, February and April 1980, the solar energy system supplied 21% of the space heating and 23% of the domestic hot water heating required for the residence. The system solar fraction averaged 22%. The solar energy system is designed to supply 41% of the heating needs of the residence during the reported months. Performance suffered this heating season primarily because of serious problems with the air handler unit.

The space heating load for the three months reported totalled 14.35 million BTU (an average of 4.78 million BTU/month).

Problems with the air handler unit had an adverse effect on system thermal performance during the heating season. The air handler unit was inoperative during December and January, and for much of February (monthly performance values for February were extrapolated using data from 12 days of correct air handler operation). In April, the air handler unit was not properly adjusted. This resulted in low air flow rates and correspondingly poor performance for that month.

The air handler unit incorporates a belt and pulley system which requires delicate adjustment to prevent it from either running too slowly and producing low air flows, or running too fast and drawing too much current. The unit is also an old model, and relatively difficult to service.

The space heating subsystem experienced some chronic, minor operational problems. One problem concerned the space heating subsystem and the storage subsystem, which are closely tied together in the following manner. The system circulates air continuously through the storage bin during space heating from either solar storage or auxiliary furnace. Circulation through storage in conjunction with auxiliary heating can occur even when the storage bin is cool. This recommended method of operation created a problem which was most evident in February 1980. During that month, particularly since the solar energy system was not always working, the storage bin was frequently cooler than room temperature; room temperature air was actually cooled as it circulated through the storage bin. This problem is significant during the colder months of the winter.

Another problem involved the auxiliary furnace. This heating season, the air handler and the furnace blowers frequently cycled on and off during auxiliary space heating. The intervals of cycling were as short as five minutes on and fifteen minutes off, though often longer. This cycling makes the system less efficient. The grantee explained that the cycling is probably due to the oversizing of the furnace.

The DHW load totalled 3.38 million BTU (an average of 1.13 million BTU/month). Hot water consumption totalled 4,883 gallons (an average of 1,628 gallons/ month, or 54 gallons/day).

In general, all solar modes - collector-to-storage with DHW, collector-to-space heating with DHW; and storage-to-space heating - plus independent auxiliary furnace operation, functioned successfully during the reporting months.

The DHW preheat loop pump operation was observed. This pump, monitored by EP300, operated when collection was taking place and shut off when the preheat tank was sufficiently heated (about 130°F), even if the energy collection subsystem was still collecting. Typical circulation through the air-water heat exchanger was under three gallons of water/minute.

The collector array maintained a 22% average efficiency (based on total solar radiation incident on the array). This is an acceptable efficiency for flat-plate air medium collectors.

The collector operation was satisfactory. The collector outlet air reached temperatures over 160°F in February and around 200°F in April. Collector air flows ranged from 600 ft^3/minute in February to 300-400 ft^3/minute in April.

The insolation per square foot incident on the collector array was typically less than the long-term average estimated values of insolation for the Seattle locale over the reporting months. This may be due to shading from the many tall trees in the nearby valley.

Besides being incident on the collector array, insolation is also admitted through the several hundred square feet of south-facing windows. This passive gain is a factor in heating the house, but current instrumentation is such that the effect cannot be quantified.

A modified f-Chart analysis, using measured subsystem loads, losses, and weather data, yielded estimates for solar energy used and solar fractions for this system. In this manner, solar energy collected was estimated at 6.78 million BTU and solar energy used was estimated at 4.10 million BTU for the three reporting months. The actual solar energy collected was 8.77 million BTU for the three months, which is higher than the predicted value. The actual solar energy used, however, was 3.76 million BTU. This is less than, but within 10% of, the predicted quantity.

The system thermal performance is summarized in Table 1.

Table 1. SOLAR SYSTEM THERMAL PERFORMANCE

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU, unless otherwise indicated)

MONTH	SOLAR ENERGY COLLECTED	SYSTEM LOAD	SOLAR ENERGY USED		AUXILIARY ENERGY		OPERATING ENERGY	ENERGY SAVINGS		SOLAR FRACTION (PERCENT)	
			PREDICTED	MEASURED	FOSSIL	THERMAL		FOSSIL	ELECTRICAL	PREDICTED	MEASURED
NOV	1.31	7.97	0.54	0.77	13.17	7.41	0.57	1.41	-0.28	7	11
FEB	3.20	5.95	1.44	1.50	8.40	4.79	0.60	2.68	-0.38	23	26
APR	4.26	3.78	2.12	1.49	5.10	2.67	0.60	2.54	-0.39	51	38
TOTAL	8.77	17.70	4.10	3.76	26.67	14.87	1.77	6.63	-1.05	-	-
AVERAGE	2.92	5.90	1.37	1.25	8.89	4.96	0.59	2.21	-0.35	22*	22*

*Weighted average.

The Washington Natural Gas Company, which owns the residence, provides improvements to the solar energy system and has been consistently cooperative with the NSDN program.

In 1978, the grantee took action to restrict air leakage from storage; leaks are a prevalent problem in air systems.

In 1980, a "lockout device" was installed in storage. This device is meant to prevent the auxiliary furnace from providing space heating if the storage bin is hot enough (greater than 100°F) to handle the load. Conclusive evidence of its proper operation was not available this heating season.

Future improvements of the system are planned:

- The grantee has de-rated the furnace for the upcoming heating season, from 125,000 BTU/hour to 95,000 BTU/hour. It is expected that this will decrease the cycling effect mentioned earlier and so reduce system waste. (An efficiency test done by the grantee rates current furnace combustion at 75% efficient, but this rating does not take into account any inefficiency in fuel consumption due to the furnace operation of cycling on and off.)
- The DHW subsystem will benefit from insulation on the piping, which the grantee plans to install in 1980.
- The Washington Natural Gas Company is also considering replacing the air handler unit with a newer model.

In March 1980, the solar energy system was deliberately shut off in order to do a heating load study on the house. Auxiliary furnace inputs and outputs continued to be monitored during this period. This study was expected to verify passive solar heating of the house. However, this method for evaluating heating load involves many unknowns, and did not conclusively prove that there is a significant passive solar contribution to space heating. In fact, several different valid values of heat loss coefficient (UA) for the house were calculated from this study. One value for the heat loss coefficient, which was based on a thermal measurement of furnace output, was 476 BTU/°F-hr.

1.2 OVERALL SYSTEM PERFORMANCE

Solar system performance this heating season was 22% of the subsystem loads. However, this is far short of the design solar fraction of 41%. Even at its best performance, in April, the system solar fraction was only 38%.

System performance would have been better if the air handler had been adjusted properly. Improper air handler adjustment was evident in April, when monitored air flows were much lower than normal.

In general, insolation in the Seattle area is low compared to most other parts of the country. For this locale, it appears that a 41% solar fraction for the three reported months is an overly-optimistic expectation for this system.

The Energy Flow Diagram in Figure 1 illustrates the flow of solar energy through the Washington Natural Gas system for the three-month period under study: November 1979 and February and April 1980. This diagram shows the amount of energy collected, transported, stored, consumed or lost at each point in the system. (Due to the extrapolated February data, some junctions of the diagram do not balance out, although there were no physical losses at these mathematical junctions.)

Figure 1 shows significant losses from storage. Energy loss from storage is apparently aggravated by the continual circulation of air through storage during all modes of space heating.

Losses at the entrance of solar energy to the DHW subsystem are expected since there is an air-water heat exchanger at this junction. Large losses from the energy collection and storage subsystem (ECSS) occur because the incident solar radiation indicated on the diagram represents all available radiation, much of which the system may not have had occasion to use.

The overall thermal performance of the solar energy system presented in Table 1 is shown graphically in Figure 2. This graphic illustration verifies expectations. In a comparison between November and April, the heating load was much larger in November and less solar solar energy was used that month. (February quantities are estimated values.) Low available insolation for this area in November partially accounts for the low solar contribution that month.

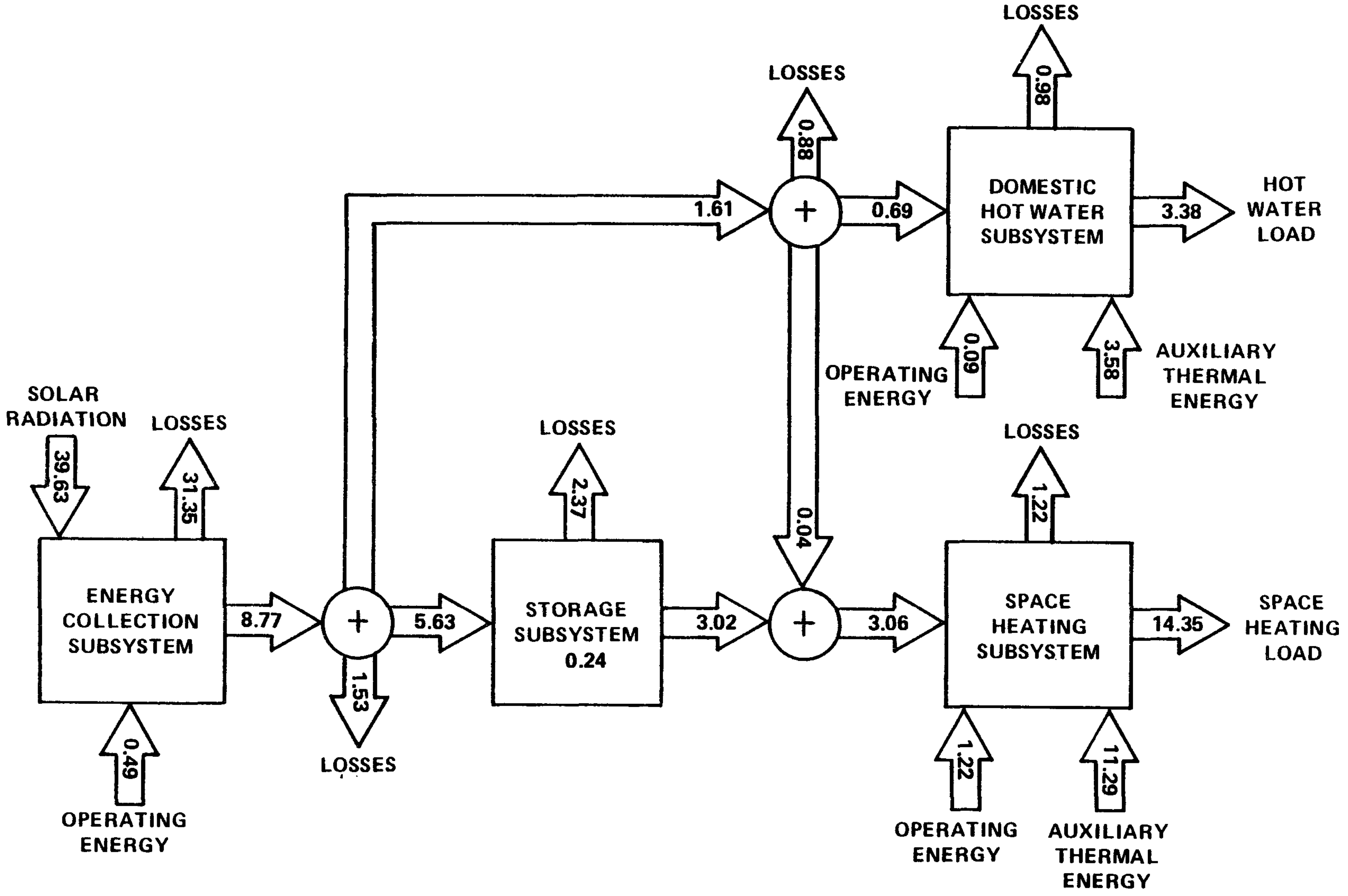
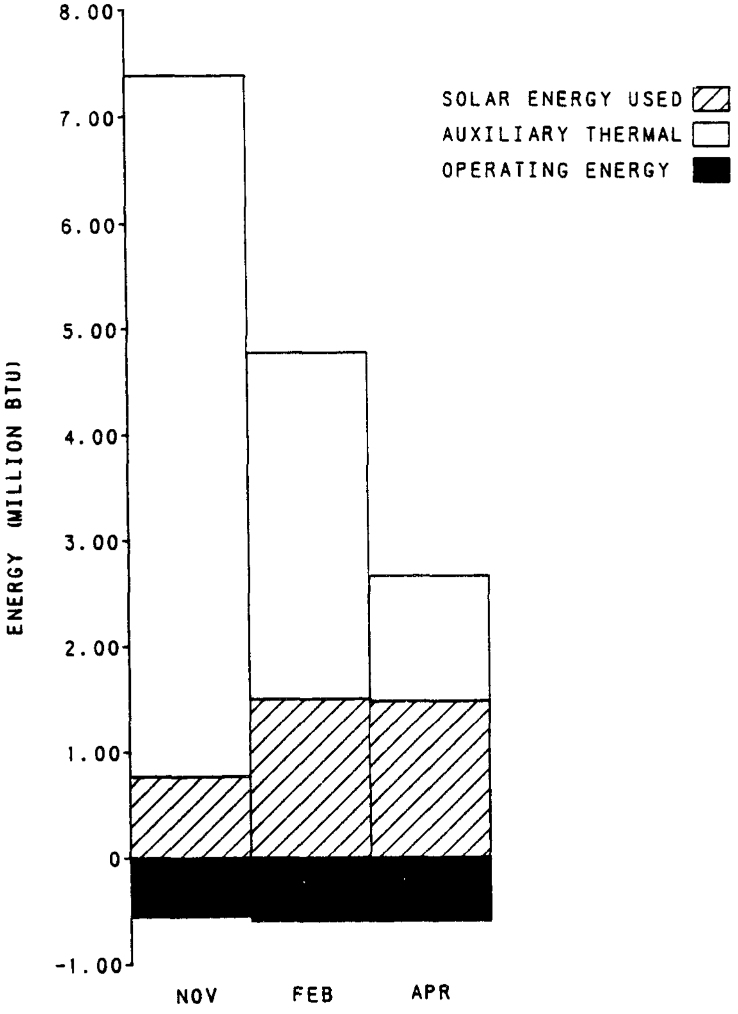


Figure 1. Energy Flow Diagram for Washington Natural Gas
November 1979, February* and April 1980
(Figures in million BTU)

*Estimated values based on 12 days' data (due to these estimates, some junctions of the flow diagram do not balance out).

The solar energy contribution in April would have been greater if the air handler had been properly adjusted for the optimum air flow rates; at it was, air flows were very low that month.



Operating energy for the system is considered a system penalty and is plotted as a negative value below the origin.

Figure 2. System Thermal Performance
Washington Natural Gas
November 1979, February and April 1980

The solar energy coefficient of performance (COP) is indicated in Table 2. The COP simply provides a numerical value for the relationship of solar energy used or collected and the energy required to collect or deliver it. The greater the COP value, the more efficient the subsystem. The solar energy system at the Washington Natural Gas site functioned at a reporting period weighted average solar energy system COP value of 3.58 for the period November 1979 and February and April 1980.

Table 2. SOLAR COEFFICIENT OF PERFORMANCE

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

MONTH	SOLAR ENERGY SYSTEM	COLLECTOR SUBSYSTEM	DOMESTIC HOT WATER SOLAR	SPACE HEATING SOLAR
NOV	2.75	13.10	5.33	4.00
FEB	3.95	21.33	6.67	6.50
APR	3.82	17.75	11.00	9.67
WEIGHTED AVERAGE	3.58	17.90	7.67	6.51

The February values are estimates but they show that the system could have done very well had it functioned the entire month the way it did for the 12 good days. (The air handler was not working for 17 days.)

The higher subsystem COP's in April reflect lower losses in April than in the winter months.

1.3 ENERGY SAVINGS

Energy savings for this site for the reporting period, November 1979, February and April 1980, are presented in Table 3 and shown graphically in Figure 3. For this three-month period, the total savings were 6.63 million BTU (for a monthly average of 2.21 million BTU). This is approximately 6,491 cubic feet of natural gas. An electrical energy expense of 1.05 million BTU was incurred during the reporting period for the operation of solar energy components. This electrical expense is approximately 308 kwh of electricity. At an estimated cost of $5.11 per 1,000 cubic feet of natural gas, and of $0.05 per kwh of electricity, this yields a net savings of $18.00 for the three months studied, or $6.00 a month.

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. Energy savings are calculated with reference to a conventional heating system; in this case, a totally gas-fired heating system is the reference for computing fossil fuel savings. The operating energy required to transport solar energy from the collector-to-storage is subtracted from the solar energy contribution to the loads to determine net savings.

The auxiliary source at the Washington Natural Gas site consists of a gas forced-air furnace and a gas-fired DHW heater. The DHW heater is considered to be 66% efficient for computational purposes.

Savings were large in February and in April because of high solar energy usage. November performance was poor because of colder weather and the resultant higher losses, and lower available sunlight. April savings could have been even greater but for the air handler problem encountered that month.

Table 3. ENERGY SAVINGS

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU)

		SOLAR ENERGY ATTRIBUTED TO						
		SPACE HEATING		DOMESTIC HOT WATER			NET ENERGY SAVINGS	
MONTH	SOLAR ENERGY USED	ELECTRICAL	FOSSIL FUEL	ELECTRICAL	FOSSIL FUEL	ECSS OPERATING ENERGY	ELECTRICAL	FOSSIL FUEL
NOV	0.77	-0.15	1.00	-0.03	0.41	0.10	-0.28	1.41
FEB	1.50	-0.20	2.18	-0.03	0.50	0.15	-0.38	2.68
APR	1.49	-0.12	1.93	-0.03	0.61	0.24	-0.39	2.54
TOTAL	3.76	-0.47	5.11	-0.09	1.52	0.49	-1.05	6.63
AVERAGE	1.25	-0.16	1.70	-0.03	0.51	0.16	-0.35	2.21

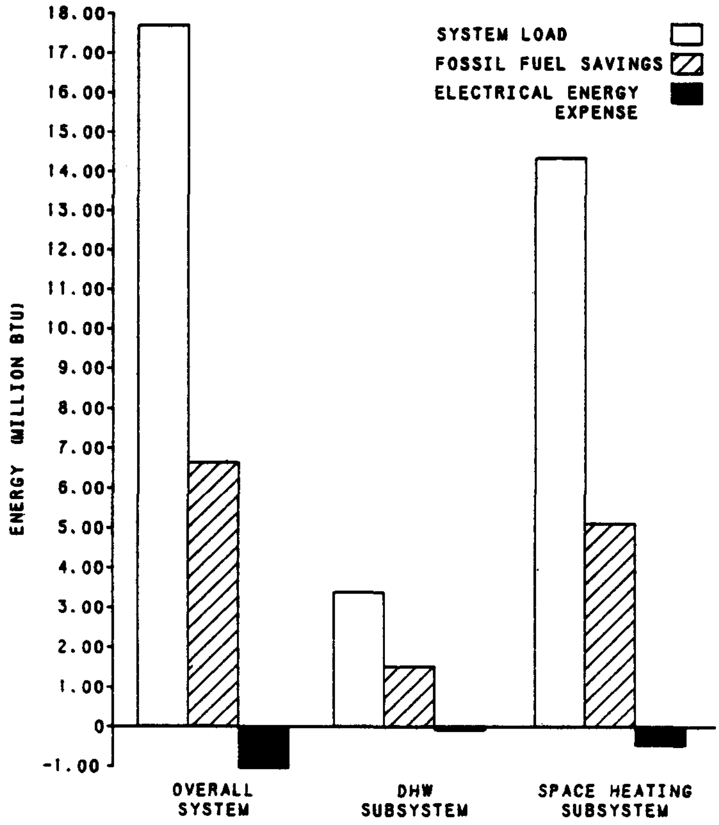


Figure 3. Combined Thermal Energy Savings Compared to Load
Washington Natural Gas
November 1979, February and April 1980

1.4 SOLAR ENERGY UTILIZATION

Figure 4 shows the use of solar energy and the percentage of losses.

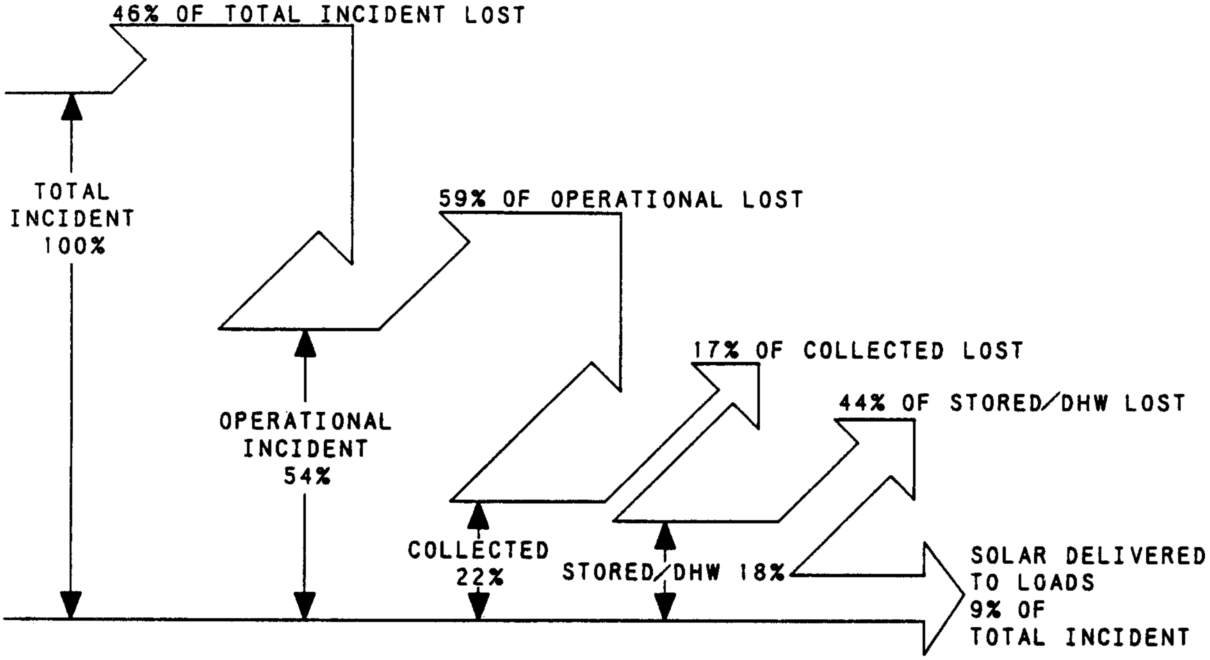


Figure 4. Solar Energy Use
Washington Natural Gas
November 1979, February and April 1980

Figure 4 shows that the system collected 22% of the total incident solar radiation. These collectors could have performed better. Correct air handler adjustment would have increased the quantity of collected energy.

Due to improper adjustment of the air handler, the system had lower-than-optimum air flows in April. This resulted in increased losses. In general, significant losses are expected in air systems because of leakage from ducts. In this system, many losses went into the unheated basement machinery room.

A high percentage of losses were from storage. The continual circulation of air through storage in the auxiliary-heating mode as well as in a solar-heating mode, and the resultant air leakage, contributed to these losses.

The relatively low percentage of incident energy that was delivered to loads, nine percent, is partly due to system problems this season, and under normal operation would be higher.

The losses of solar energy at the different stages through the system, from incident radiation to the load, are also presented in Table 4.

High percentage losses from collector subsystem to the DHW subsystem, as indicated in Table 4, partly reflect air-water heat exchanger inefficiency.

Table 4. SOLAR ENERGY LOSSES

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

	MONTHS		
	NOV	FEB	APR
1. SOLAR ENERGY (SE) COLLECTED MINUS SE DIRECTLY TO LOADS (million BTU)	1.08	2.64	3.44
2. SE TO STORAGE (million BTU)	0.80	2.05	2.78
3. LOSS - COLLECTOR TO STORAGE (%)	21	18	15
4. CHANGE IN STORED ENERGY (million BTU)	-0.26	0.23	0.27
5. LOSS FROM STORAGE (%)	59	26	50
6. HOT WATER SOLAR ENERGY (HWSE) FROM COLLECTOR SUBSYSTEM (million BTU)	0.23	0.56	0.82
7. LOSS - COLLECTOR SUBSYSTEM TO HWSE (%)	22	59	56
8. HEATING SOLAR ENERGY (HSE) FROM STORAGE (million BTU)	0.59	1.30	1.13

1.5 SYSTEM AVAILABILITY

The solar system was operational except during the following periods:

- December 1979 - Air handler breakdown
- January 1980 Air handler breakdown
- February 1980 (17 days) - Air handler breakdown
- March 1980 - System down for heating load study

The primary problem encountered this heating season, which ran from November 1979 through April 1980, was the breakdown of the air handler unit. The air handler unit, which incorporates a delicately adjusted belt and pulley system, was broken in December, January, and for 17 days in February. These breakdowns rendered the solar energy system totally ineffective. (In April, the air handler unit was out of adjustment, resulting in low air flow rates; the solar energy system functioned, but beneath its capacity.)

In March, the solar energy system was deliberately shut off for a one-month heating load study using auxiliary furnace output measurements.

SECTION 2

SUBSYSTEM PERFORMANCE

2.1 COLLECTOR

The Washington Natural Gas collector array is composed of 28 Solaron Series 2,000 flat-plate collector panels, which use air as the heat transfer fluid. Total gross collector area is 591 ft^2 (546 ft^2 net area). The array faces south and is tilted at 57 degrees from the horizontal.

The total measured solar energy incident on the collector array was 39.63 million BTU and 21.21 million BTU were incident on the array while the collector subsystem was operating. Total solar energy collected was 8.77 million BTU for a collector array efficiency of 22% based on the total incident solar energy, or 42% based on operational incident solar energy. The collected solar energy delivered directly to the space heating and domestic hot water loads was 1.61 million BTU. The collected solar energy delivered, instead, to storage was 5.63 million BTU. Transport losses incurred between solar energy collected and solar energy delivered to storage and loads were 1.53 million BTU, or 17% of the collected solar energy. The operating energy required to support the collector subsystem was 0.49 million BTU. (See Table 5.) The operating energy for the collector subsystem is the energy required to drive the air handler unit when the system is in the collector-to-storage mode.

Table 5. COLLECTOR SUBSYSTEM PERFORMANCE

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU, unless otherwise indicated)

MONTH	INCIDENT SOLAR RADIATION	COLLECTED SOLAR ENERGY	COLLECTOR SUBSYSTEM EFFICIENCY (%)	OPERATIONAL INCIDENT ENERGY	OPERATIONAL COLLECTOR EFFICIENCY (%)	ECSS OPERATING ENERGY	SOLAR ENERGY DIRECTLY TO LOADS	SOLAR ENERGY TO STORAGE	DAYTIME AMBIENT TEMPERATURE (°F)
NOV	9.13	1.31	14	2.93	45	0.10	0.18	0.80	47
FEB	12.35	3.20	26	7.00	46	0.15	0.20	2.05	47
APR	18.15	4.26	24	11.28	38	0.24	0.36	2.78	58
TOTAL	39.63	8.77	-	21.21	-	0.49	0.74	5.63	-
AVERAGE	13.21	2.92	22*	7.07	42*	0.16	0.25	1.88	51

*Weighted average.

The collector efficiency depends on the available insolation, the correct functioning of system components, the temperature of the storage bin, and the heating load called for by the residence. The collector efficiency would have been better but was affected by air handler adjustment problems, which caused low air flow rates in April.

The ECSS operating energy of 0.49 million BTU is equivalent to 144 kwh of electricity. At a rate of $0.05/kwh, this is a cost of $7.00 to run the ECSS, or about $2.00/month.

2.2 STORAGE

Storage performance data for the site for the reporting period are shown in Table 6.

During the reporting period, total solar energy delivered to storage was 5.63 million BTU. There were 3.02 million BTU delivered from storage to the space heating subsystem. Energy loss from storage was 2.38 million BTU. This loss represented 42% of the energy delivered to storage. The storage efficiency was 58%. (See Footnote 1.)

---

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

$$\mathrm{STEFF} = (\mathrm{STECH} + \mathrm{STEO})/\mathrm{STEI}$$

Where: STEFF = Storage efficiency

STECH = Change in stored energy

STEO = Energy removed from storage

STEI = Energy added to storage

Effective storage heat loss coefficient (c) for the storage subsystem can be defined as follows:

$$c = (\mathrm{STEI}-\mathrm{STEO}-\mathrm{STECH})/\ (T_s - T_a) \times t \quad \frac{\mathrm{BTU}}{\mathrm{Hr}\ {}^\circ\mathrm{F}}$$

Where: c = effective storage heat loss coefficient

T_s = average storage temperature

T_a = average ambient temperature in the vicinity of storage

t = number of hours in the month

Solar energy is stored in an underground concrete and wood rock bin with a volume of about 273 cubic feet. This bin is capable of holding roughly 27,300 pounds of stones. Storage provides heat for space heating, but not for the DHW subsystem.

The storage tank is utilized during both solar space heating and auxiliary space heating modes. By system design, air is circulated through the solar storage bin during auxiliary space heating. In this manner, a cool storage bin may drain energy from the heated space to be lost to the outside. Any such backwards delivery of energy into the storage bin is subtracted out of the measurement of energy delivered from solar storage. This is a problem during the colder months of the winter. This effect was noticed in February, but does not show up in the estimate for storage efficiency that month, which was 73% (see Table 6). Low air flow rates in April adversely affected storage efficiency that month.

Table 6. STORAGE PERFORMANCE

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU unless otherwise indicated)

MONTH	ENERGY TO STORAGE	ENERGY FROM STORAGE	CHANGE IN STORED ENERGY	STORAGE EFFICIENCY (%)	AVERAGE STORAGE TEMP. (°F)	LOSS FROM STORAGE
NOV	0.80	0.59	-0.26	41	70	0.47
FEB	2.05	1.30	0.23	73	80	0.53
APR	2.78	1.13	0.27	50	94	1.38
TOTAL	5.63	3.02	0.24	-	-	2.38
AVERAGE	1.88	1.01	0.08	58*	81	0.79

*Weighted average.

2.3 DOMESTIC HOT WATER (DHW)

The DHW subsystem includes an 80-gallon preheat tank and a conventional 50-gallon DHW tank with a gas-fired heater. Solar heated air passes through the DHW heat exchanger on its way to space heating or to storage, while a pump on the DHW side circulates water through the heat exchanger to the preheat tank.

The DHW subsystem performance for the Washington Natural Gas site for the reporting period is shown in Table 7 and presented graphically in Figure 5.

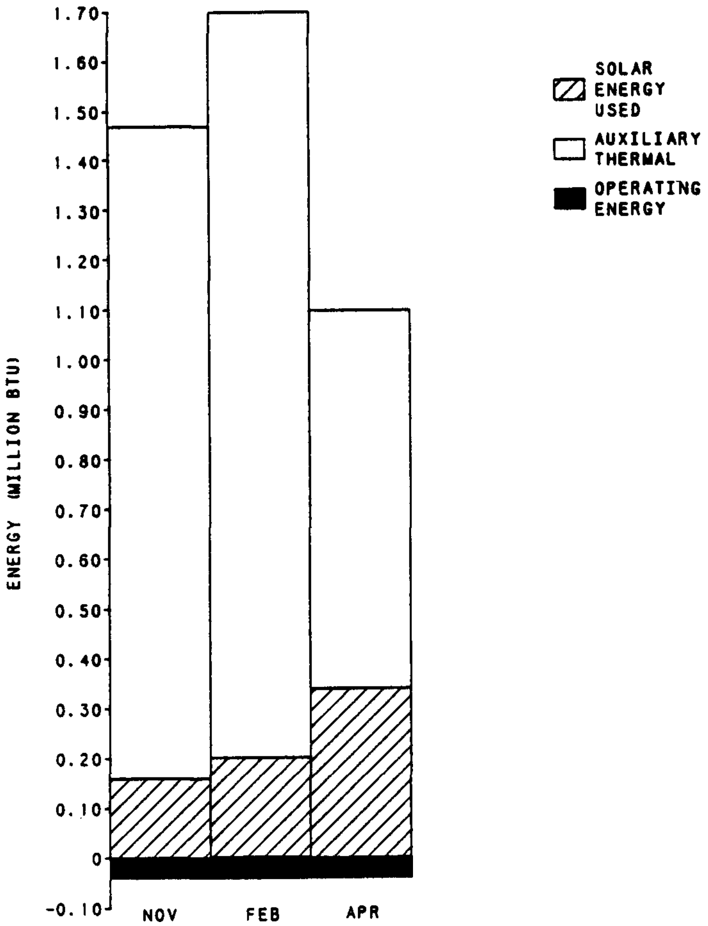
Table 7. DOMESTIC HOT WATER SUBSYSTEM PERFORMANCE

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU, unless otherwise indicated)

		ENERGY CONSUMED						
			AUXILIARY					
MONTH	DHW LOAD	SOLAR	FOSSIL	THERMAL	OPERATING EXPENSE	SOLAR FRACTION (%)	HOT WATER CONSUMPTION (GAL.)	AVERAGE HOT WATER TEMPERATURE (°F)
NOV	1.31	0.16	1.99	1.31	0.03	18	1,943	136
FEB	1.35	0.20	2.28	1.50	0.03	20	1,835	136
APR	0.72	0.33	1.17	0.77	0.03	40	1,105	132
TOTAL	3.38	0.69	5.44	3.58	0.09	-	4,883	-
AVERAGE	1.13	0.23	1.81	1.19	0.03	23*	1,628	135

*Weighted average.



Operating energy for the system is considered a system penalty and is plotted as a negative value below the origin.

Figure 5. DHW Subsystem Performance
Washington Natural Gas
November 1979, February and April 1980

The DHW subsystem required 0.69 million BTU of solar energy and 5.44 million BTU of auxiliary fossil fuel energy, or 3.58 million BTU of auxiliary thermal energy, to satisfy a hot water load of 3.38 million BTU. The solar fraction of this load was 23%, with an operating energy of 0.09 million BTU. Losses from the DHW subsystem were 0.98 million BTU. A daily average of 54 gallons of DHW was consumed at an average temperature of 135°F.

The DHW subsystem fossil fuel energy savings were 1.52 million BTU at an electrical energy expense of 0.09 million BTU. This is equivalent to a savings of 1,488 cubic feet of natural gas at the expense of 26 kwh of electrical energy. At a rate of $5.11 per 1,000 cubic feet of natural gas and $0.05 per kwh, this yields a net cost savings of $6.00, or $2.00 a month.

The DHW subsystem functioned successfully and the preheat loop pump was efficiently coordinated with the airside system functioning. Losses occur at the air-water heat exchanger junction. Losses which affected DHW subsystem performance as indicated in Table 7 include losses from exposed, uninsulated DHW plumbing. There are plans under study for insulation of DHW pipes, as of the end of this heating season.

As expected, the most solar energy was used in April, the warmest and sunniest month, even though hot water usage was least then (see Table 7).

The entire solar energy system was at a noticeable disadvantage in April because of the previously-mentioned air handler problem. In that month, at least, the DHW subsystem solar fraction could have been higher.

2.4 SPACE HEATING

Space heating is accomplished either by direct circulation of air from the collectors, or from the solar storage bin, or by the auxiliary furnace in conjunction with air circulation through storage.

The space heating performance for the Washington Natural Gas site for the reporting period is shown in Table 8 and presented graphically in Figure 6.

The space heating load of 14.35 million BTU was satisfied by 3.06 million BTU of solar energy and 11.29 million BTU of auxiliary energy. The solar fraction of this load was 21% with an operating energy expense of 1.22 million BTU.

The fossil fuel energy savings were 5.11 million BTU at an electrical energy expense of 0.47 million BTU. This is equivalent to a savings of 5,003 cubic feet of natural gas at the expense of 138 kwh of electricity. At a rate of $5.11 per 1,000 cubic feet of natural gas and $0.05 per kwh, this yields a net cost savings of $19.00, or $6.00 a month. The average building temperature for the season (November 1979, February and April 1980) was 70°F.

Space heating was affected in February by the loss of auxiliary heat during circulation of room air through the often cool solar storage tank. However, the quantities in Table 8 for February, which are estimates, do not reflect this inefficiency. Cold weather and low insolation were responsible for the heavy draw on auxiliary energy in November (see Figure 6). The April space heating solar fraction was 38% (see Table 8) but could have been higher, had it not been for the air handler problem that month (see Summary and Conclusions).

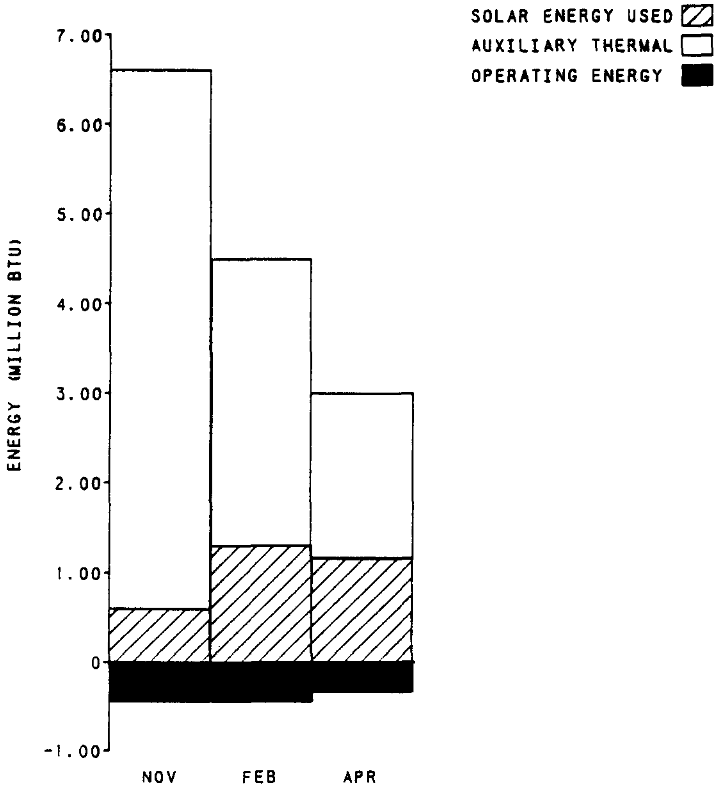
Table 8. SPACE HEATING SUBSYSTEM PERFORMANCE

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU, unless otherwise indicated)

		ENERGY CONSUMED						
MONTH	SPACE HEATING LOAD	SOLAR	AUXILIARY THERMAL	AUXILIARY EFFICIENCY (%)	AUXILIARY FOSSIL	OPERATING ENERGY	SOLAR FRACTION (%)	BUILDING TEMPERATURE (°F)
NOV	6.69	0.60	6.09	54	11.18	0.44	9	69
FEB	4.60	1.30	3.30	54	6.13	0.45	28	69
APR	3.06	1.16	1.90	48	3.93	0.33	38	71
TOTAL	14.35	3.06	11.29	-	21.24	1.22	-	-
AVERAGE	4.78	1.02	3.76	53*	7.08	0.41	21*	70

*Weighted average.



Operating energy for the system is considered a system penalty and is plotted as a negative value below the origin.

Figure 6. Space Heating Subsystem Performance
Washington Natural Gas
November 1979, February and April 1980

Table 9 contains results pertaining to a heating load study done on the residence. A standard method for estimating heating load for the month is used in this table. This method involves multiplying a derived value for a building heat loss coefficient (UA) by the number of heating degree-days that month, to arrive at a Design Heat Load. This Design Heat Load is compared with the Measured Load (based on furnace output for that month) and the difference is indicated as Possible Space Heating Gains. The UA value used, 476 BTU/hr-°F, was the result of the building heating load study done in March 1980. (For this study, the solar energy system was temporarily shut down, and auxiliary furnace monitoring was utilized to figure auxiliary energy usage.) Resulting Design Heat Load values are reasonably close to Measured Load values. Design Heat Load values are higher, though, which implies that some of the building heat may be handled by unmeasured heat sources, i.e., internal heating from appliances, passive solar gain, etc.

Table 9. DESIGN HEATING LOAD BY UA x Cd METHOD

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

MONTH	BUILDING TEMPERATURE (°F)	AMBIENT TEMPERATURE (°F)	HEATING DEGREE-DAYS (65°F Ref)	UA x Cd VALUE (BTU/hr-°F)	DESIGN HEAT LOAD (BTU x 10^6)	MEASURED LOAD (BTU x 10^6)	POSSIBLE SPACE HEATING GAINS (BTU x 10^6)
NOV	69	44	634	476	7.24	6.69	0.55
FEB	69	45	590	476	6.74	4.60	2.14
APR	71	52	394	476	4.50	3.06	1.44
TOTAL	-	-	1,618	-	18.48	14.35	4.13
AVERAGE	70	47	539	476	6.16	4.78	1.38

SECTION 3

OPERATING ENERGY

Total operating energy for the Washington Natural Gas site is the electrical energy required to support the space heating and DHW subsystems without affecting their thermal states.

Energy collection and storage subsystem operating energy consists of the air handler unit power measured while the system is in the collector-to-storage mode. This operating energy is totally solar specific.

Heating subsystem operating energy consists of the sum of the air handler unit power plus the furnace fan power, measured whenever the system is providing space heating. The solar specific part of the heating subsystem operating energy includes only the air handler unit power measured whenever the system is providing space heating.

Domestic hot water subsystem operating energy includes only the hot water preheat loop pump power. This operating energy is totally solar-specific.

Measured monthly values of the Washington Natural Gas solar energy system and subsystem operating energy for the report period are presented in Table 10. A total of 1.77 million BTU of operating energy was consumed by the entire system during the reporting period. A distribution of this operating energy among the subsystems is illustrated in Figure 7. Operating energy was relatively consistent in magnitude over the three-month reporting period.

Figure 8 shows a distribution of solar unique operating energy for this heating season. The large percentage for the space heating subsystem is because of the continual use of the air handler during all space heating modes.

Table 10. OPERATING ENERGY

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU)

MONTH	ECSS OPERATING ENERGY (SOLAR UNIQUE)	DHW OPERATING ENERGY		SHS OPERATING ENERGY		TOTAL SOLAR UNIQUE OPERATING ENERGY	TOTAL SYSTEM OPERATING ENERGY
		TOTAL	SOLAR UNIQUE	TOTAL	SOLAR UNIQUE		
NOV	0.10	0.03	0.03	0.44	0.15	0.28	0.57
FEB	0.15	0.03	0.03	0.45	0.20	0.38	0.60
APR	0.24	0.03	0.03	0.33	0.12	0.39	0.60
TOTAL	0.49	0.09	0.09	1.22	0.47	1.05	1.77
AVERAGE	0.16	0.03	0.03	0.41	0.16	0.35	0.59

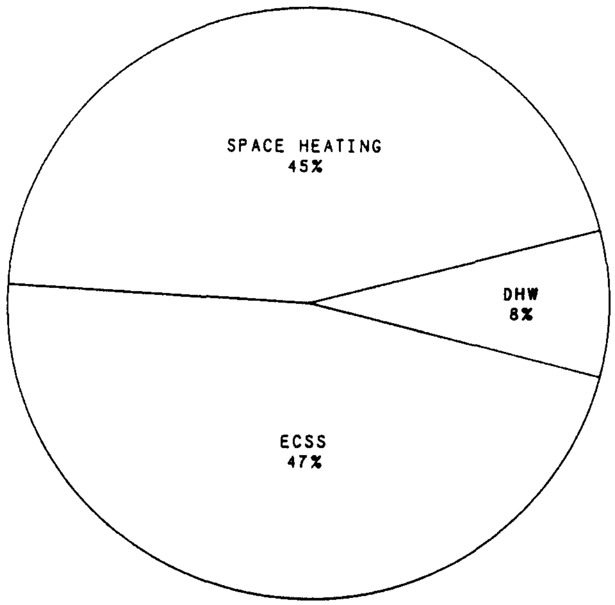


Figure 7. Solar-Unique Operating Energy Distribution
Washington Natural Gas
November 1979, February and April 1980

SECTION 4

WEATHER CONDITIONS

The Washington Natural Gas solar energy system is located in Kirkland, Washington at 47 degrees N latitude and 122 degrees W longitude.

Monthly values of the total solar energy incident in the plane of the collector array and the average outdoor temperature measured at the site during the reporting period are presented in Table 11. Also presented in the table are the corresponding long-term average monthly values of the measured weather parameters. 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 converted to collector angle and azimuth orientation.

Table 11. WEATHER CONDITIONS

WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

	DAILY INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/FT^2-DAY)		AMBIENT TEMPERATURE (°F)		HEATING DEGREE-DAYS	
MONTH	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE
NOV	557	613	44	45	634	612
FEB	754	771	45	42	590	636
APR	1,108	1,290	52	49	394	489
TOTAL	-	-	-	-	1,618	1,737
AVERAGE	806	891	47	45	539	579

During the period of November 1979 and February and April 1980, the average daily total incident solar radiation on the collector array was 806 BTU per square foot per day. This radiation was below the estimated average daily solar radiation for this geographical area during the reporting period of 891

BTU per square foot per day for a south-facing plane with a tilt of 57 degrees to the horizontal. During the period, the highest monthly average insolation was 1,108 BTU per square foot per day during April. The average ambient temperature during the reporting period was 47°F as compared with the long-term average for the period of 45°F. The highest monthly average ambient temperature was 52°F during April and the lowest monthly average ambient temperature was 44°F during November. The total number of heating degree-days for the period (based on a 65°F reference) was 1,618 as compared with the long-term average of 1,737. The range of heating degree-days was from a high of 634 during November to a low of 394 during April.

Extraterrestrial radiation values are computed (see Footnote 1) and given in the table below for each month during the period. The ratio of total insolation on a tilted surface to extraterrestrial radiation on a parallel surface is called the clearness index.

This parameter quantifies the effects of cloudiness and atmospheric transmission on the insolation received at the earth's surface. The clearness index was highest in April 1980 at 37% and was 16% in February 1980. November 1979 data was not available.

	NOV	FEB	APR
Extraterrestrial Insolation on tilted surface (BTU/ft^2-day)	*	3,195	3,070
$\frac{\text{TTL INS}}{\text{EXT INS}}$ (%)	*	16	37

*Denotes unavailable data.

For a more complete set of meteorological data see Appendix F, which contains daily average values for the months of the reporting period.

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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.

SECTION 5

REFERENCES

*1. National Solar Data Network, Department of Energy, prepared under Contract Number DE-AC01-79CS30027, Vitro Laboratories, Silver Spring, Maryland, January 1980.

2. J. T. Smok, V. S. Sohoni, J. M. Nash, "Processing of Instrumented Data for the National Solar Heating and Cooling Demonstration Program," Conference on Performance Monitoring Techniques for Evaluation of Solar Heating and Cooling Systems, Washington, D.C., April 1978.

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

4. Mears, J. C., Reference Monthly Environmental Data for Systems in the National Solar Data Network. Department of Energy report SOLAR/0019-79/36, Washington, D.C., 1979.

5. ASHRAE Standard 93-77, Methods of Testing to Determine the Thermal Performance of Solar Collectors, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, N.Y., 1977.

6. ASHRAE Standard 94-77, Methods of Testing Thermal Storage Devices Based on Thermal Performance, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, N.Y., 1977.

*6A. User's Guide to Monthly Performance Reports, June 1980, SOLAR/0004-80/18, Vitro Laboratories, Silver Spring, Maryland.

*6B. Instrumentation Installation Guidelines July 1980, Parts 1, 2, and 3, SOLAR/0001-80/15, Vitro Laboratories, Silver Spring, Maryland.

*7. Monthly Performance Report, Washington Natural Gas, February 1980, SOLAR/1002-80/02, Vitro Laboratories, Silver Spring, Maryland.

*8. Monthly Performance Report, Washington Natural Gas, April 1980, SOLAR/1002-80/04, Vitro Laboratories, Silver Spring, Maryland.

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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

SYSTEM

The Washington Natural Gas Company site is a single family residence in Kirkland, Washington. The home has approximately 2,607 square feet of conditioned space. Solar energy is used for space heating the home and preheating domestic hot water (DHW). The solar energy system has an array of flat-plate collectors with a gross area of 591 square feet. The array faces south at an angle of 57 degrees to the horizontal. Air is used as the medium for delivering solar energy from the collector array to storage and to the space heating and hot water loads. Solar energy is stored underground in a 273 cubic foot bin containing 27,300 pounds of smooth stones. The bin has two inches of styrofoam insulation. Preheated city water is stored in an 80-gallon preheat storage tank and supplied, on demand, to a conventional 50-gallon DHW tank. When solar energy is insufficient to satisfy the space heating load, a gas furnace provides auxiliary energy for space heating. Similarly, a gas-fired unit in the DHW tank provides auxiliary energy for water heating.

Substantial south-facing window area and a thermally efficient design allow for a passive solar contribution to space heating. The extent of this passive solar effect, and whether it actually decreases the efficiency of the active system, is currently under investigation.

The manufacturer of the flat-plate collector array and the associated controls unit is the Solaron Corporation of Denver, Colorado.

The system, shown schematically, has four modes of solar operation:

Mode 1 - Collector-to-Storage - This mode activates when there is no demand for space heating, and the temperature of the collector outlet exceeds that of the solar energy storage bin as measured by the control system sensors. Air circulates from the collector, through the air-to-liquid heat exchanger, through the air-handling unit, and then through the solar energy storage bin to the collector. This mode exists as long as the temperature of the storage bin does not exceed 140°F.

Mode 2 - Storage-to-Space Heating - This mode activates when space heating is required, the solar insolation is insufficient to furnish the required energy from the collector, and the temperature of the solar energy storage bin is higher than 90°F, as indicated by the control system sensors. Air circulates from the solar energy storage bin, through the air-handling unit and gas furnace, then returns to the storage bin, bypassing the collectors.

Mode 3 - Collector-to-DHW Tank - This mode activates during the summer when the collector outlet temperature is higher than the temperature of the water in the preheat tank as indicated by the control system sensors. Air circulates from the collector, through the air-to-liquid heat exchanger and the air-handling unit, and returns to the collectors, bypassing the solar energy storage bin. Domestic water preheating also occurs in modes 1 and 4.

Mode 4 - Collector-to-Space Heating - This mode activates when the collector is operating, and the plenum temperature at the top of storage as indicated by the control system sensors is higher than a minimum value suitable for supplying heat to the house. Heated air is circulated through the house by the air-handling unit before being returned to the collector.

SUBSYSTEMS

Collector - The gross collector array area (about 21 square feet gross area per panel for 28 panels) is 591 square feet. The net collector array area used is 546 square feet. The collectors face south and are tilted to an altitude angle of 57 degrees from the horizontal. Orientation of the collectors is close to the optimum orientation for a system of this type, at a site latitude of 47 degrees North. Optimum collector orientation at this site is estimated to be due South at a tilt of 57 to 62 degrees. The collectors are positioned up high, over a cliff, but nearby tall trees are believed to cause shading problems.

The collector panels are Solaron series 2,000 flat-plates with two glass covers and a nonselective absorber surface. The absorber surface has a solar absorptivity of 0.92 and an infrared emissivity of 0.89. Total solar transmissivity of the glazing is 0.81. The absorber surface is composed of black paint on black porcelain enamel. Air is the medium circulated through the collectors.

Storage - Solar energy storage is provided by an underground concrete and wood rock bin located in the basement machinery room of the building. The bin is about eight feet by six feet by six feet high and only the top one foot is aboveground. The bin contains a volume of about 288 cubic feet, of which 273 cubic feet are filled with 27,300 pounds of smooth stones. The storage has two inches of styrofoam insulation, one inch of fiberglass insulation, and wood over the top. Air is used as the medium to transfer solar energy to the space heating subsystem. Preheated city water is also stored in an 80-gallon preheat tank for use in the DHW subsystem.

Space Heating - The space heating subsystem is designed to utilize solar energy from the collectors or the storage bin using an air handling unit. The system has a Payne forced-air gas-fired furnace, model 125U48, designed to deliver 0.125 million BTU/hour to satisfy the building heat load. The design solar fraction is 48%.

Hot Water - City water is preheated and stored in an 80-gallon storage tank and supplied, on demand, to a conventional 50-gallon DHW tank. When solar energy is insufficient to satisfy the DHW load, a gas heater in the DHW tank provides auxiliary energy for heating the supply water. Solar energy is transferred from the collectors to the DHW tank during collector-to-storage or collector-to-space-heating operation through a heat exchanger. Water is used as the transfer medium to deliver energy to the preheat tank.

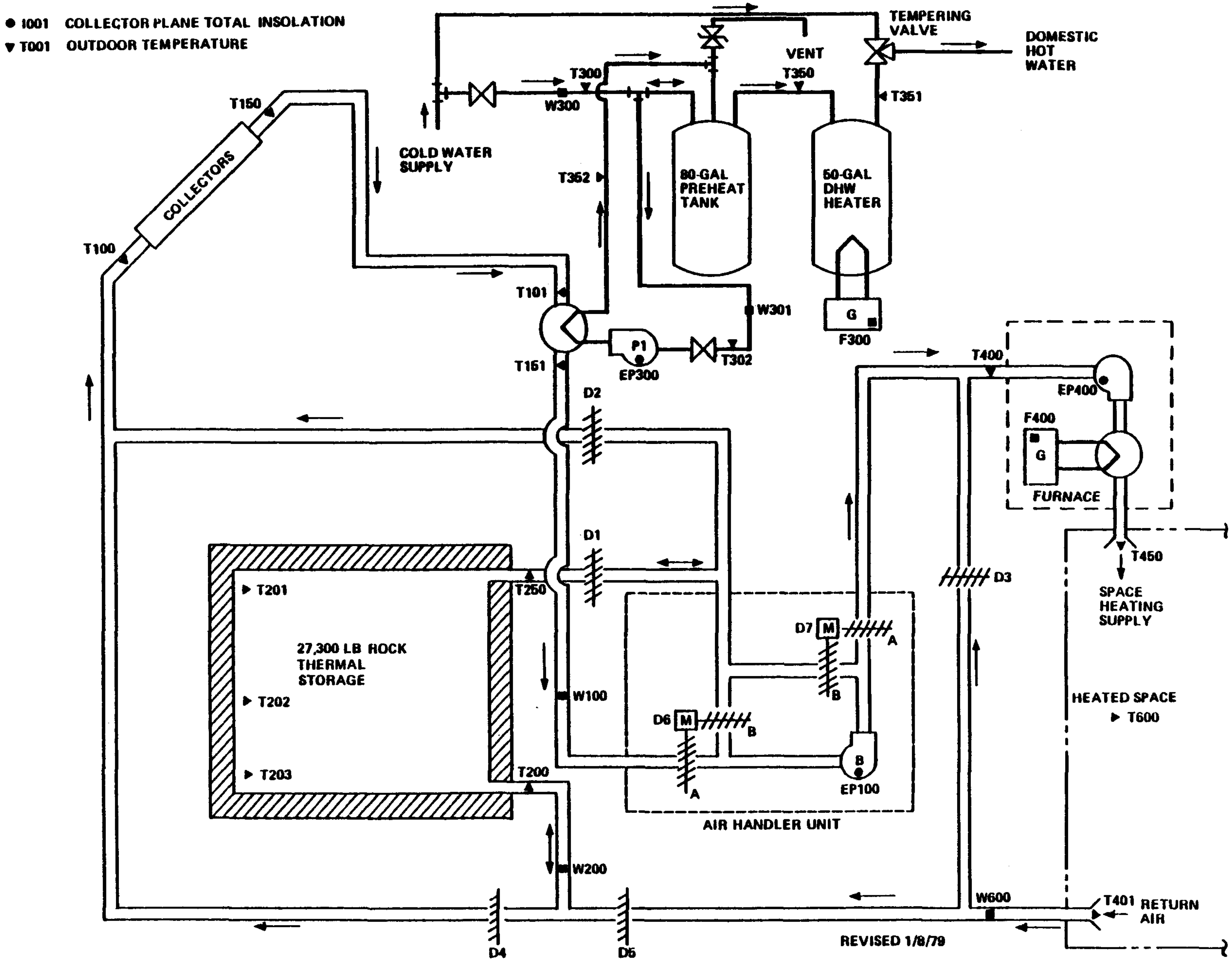

Figure A-1. Washington Natural Gas Solar Energy System Schematic

APPENDIX B

PERFORMANCE EVALUATION TECHNIQUES

The performance of the Washington Natural Gas solar energy system is evaluated by calculating a set of primary performance factors which are based on those in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" (NBSIR-76/1137).

An overview of the NSDN data collection and dissemination process is shown in Figure B-1.

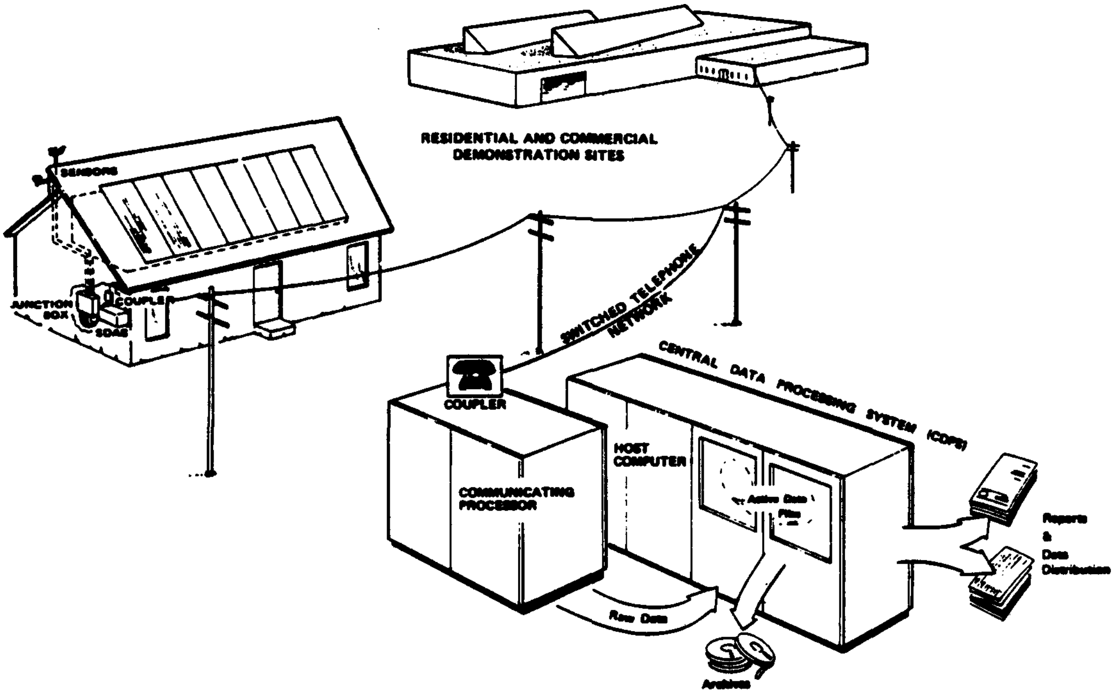

Figure B-1. The National Solar Data Network

DATA COLLECTION AND PROCESSING

Each site contains standard industrial instrumentation modified for the particular site. Sensors measure temperatures, flows, insolation, electric power, fossil fuel usage, and other parameters. These sensors are all wired into a junction box (J-box), which is in turn connected to a micro-processor data logger called the Site Data Acquisition Subsystem (SDAS). The SDAS can read up to 96 different channels, one channel for each sensor. The SDAS takes the analog voltage input to each channel and converts it to a 10-bit word. At intervals of five minutes (actually every 320 seconds) the SDAS samples each channel and records the values on a cassette tape. Some of the channels can be sampled 10 times in each five-minute period, and the average value is recorded in the tape.

Each SDAS is connected through a modem to voice-grade telephone lines which are used to transmit the data to a central computer facility. This facility is the Central Data Processing System (CDPS), located at Vitro Laboratories in Silver Spring, Maryland. The CDPS hardware consists of an IBM System 7, an IBM 370/145, and an IBM 3033. The System 7 periodically calls up each SDAS in the system and has the SDAS transmit the data on the cassette tape back to the System 7. Typically, the System 7 collects data from each SDAS six times a week, although the tape can hold three to five days of data, depending on the number of channels.

The data received by the System 7 are in the form of digital counts in the range of 0-1023. These counts are then processed by software in the CDPS, where they are converted from counts to engineering units (EU) by applying appropriate calibration constants. The engineering unit data called "detailed measurements" in the software are then tabulated on a daily basis for the site analyst, and these tabulations are also called "tab data." The CDPS is also capable of transforming this data into plots or graphs.

Solar system performance reports present system parameters as monthly values. If some of the data during the month is not collected due to solar system, instrumentation system, or data acquisition problems, or if some of the collected data is invalid, then the collected valid data is extrapolated to provide the monthly performance estimates. Researchers and other users who require unextrapolated, "raw" data may obtain such by contacting Vitro Laboratories.

DATA ANALYSIS

The analyst develops a unique set of "site equations" (given in Appendix D) for each site in the NSDN, following the guidelines presented herein.

The equations calculate the flow of energy through the system, including solar energy, auxiliary energy, and losses. These equations are programmed in PL/1 and become part of the Central Data Processing System. The PL/1 program for each site is termed the site software. The site software processes the detailed data, using as input a "measurement record" containing the data for each five-minute period. The site software produces as output a set of performance factors; on an hourly, daily, and monthly basis.

These performance factors (Appendix C) quantify the thermal performance of the system by measuring energy flows throughout the various subsystems. The system performance may then be evaluated based on the efficiency of the system in transferring these energies.

Performance factors which are considered to be of primary importance are those which are essential for system evaluation. Without these primary performance factors (which are denoted by an asterisk in Appendix C), comparative evaluation of the wide variety of solar energy systems would be impossible. An example of a primary performance factor is SECA - Solar Energy Collected by the Array. This is quite obviously a key parameter in system analysis.

Secondary performance factors are data deemed important and useful in comparison and evaluation of solar systems, particularly with respect to component interactions and simulation. In most cases these secondary performance factors are computed as functions of primary performance factors.

There are irregularly occurring cases of missing data as is normal for any real time data collection from mechanical equipment. When data for individual scans or whole hours are missing, values of performance factors are assigned which are interpolated from measured data. If no valid measured data are available for interpolation, a null value is assigned. If data are missing for a whole day, each hour is interpolated separately. Data are interpolated in order to provide solar system performance factors on a whole hour, whole day and whole month basis for use by architects and designers.

REPORTING

The performance of the Washington Natural Gas solar energy system during November 1979, February and April 1980 was analyzed during the heating season, and Monthly Performance Reports were published for the months when sufficient valid data were available. See the following page for a list of these reports.

In addition, data are included in this report which are not in Monthly Performance Reports.

OTHER DATA REPORTS ON THIS SITE*

Monthly Performance Reports:

- August 1978, SOLAR/1002-78/08
- September 1978, SOLAR/1002-78/09
- October 1978, SOLAR/1002-78/10
- December 1978, SOLAR/1002-78/12
- January 1979, SOLAR/1002-79/01
- February 1979, SOLAR/1002-79/02
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* These reports can be obtained (free) by contacting: U.S. Department of Energy, Technical Information Center, P.O. Box 62, Oak Ridge, TN 37830.

APPENDIX C

PERFORMANCE FACTORS AND SOLAR TERMS

The performance factors identified in the site equations (Appendix D) by the use of acronyms or symbols are defined in this Appendix in Section 1. Appendix C includes the symbol, the actual name of the performance factor, and a short definition.

Section 2 contains a glossary of solar terminology, in alphabetical order. These terms are included for quick reference by the reader.

Section 3 describes abbreviations used in this report.

Section 1.	Performance Factor Definitions
Section 2.	Solar Terminology
Section 3.	Abbreviations

SECTION 1. PERFORMANCE FACTOR DEFINITIONS

SYMBOL	NAME	DEFINITION
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.
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.
CAT	SCS Auxiliary Thermal Energy	Amount of energy provided to the SCS by a BTU heat transfer fluid from an auxiliary source.
* CL	Space Cooling Subsystem Load	Energy required to satisfy the temperature control demands of the space cooling subsystem.
COPE	SCS Operating Energy	Amount of energy required to support the SCS operation which is not intended to be applied directly to the SCS load.
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.

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* Primary Performance Factors

SYMBOL	NAME	DEFINITION
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	Portion of the SCS load which is supported by solar energy.
CSOPE	ECSS Operating Energy	Amount of energy used to support the ECSS operation (which is not intended to be supplied to the ECSS thermal state).
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 loads.
HAE	SHS Auxiliary Electrical Fuel Energy	Amount of electrical energy provided to the SHS to be converted and applied to the SHS load.
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 energy provided to the SHS by a heat transfer fluid from an auxiliary source.
* HL	Space Heating Subsystem Load	Energy required to satisfy the temperature control demands of the space heating subsystem.

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* Primary Performance Factors

SYMBOL	NAME	DEFINITION
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).
HOURCT	Record Time	Count of hours elapsed from the start of 1977.
* HSFR	SHS Solar Fraction	Portion of the SHS load which is supported by solar energy.
HSE	Solar Energy to SHS	Amount of solar energy delivered to the SHS.
* 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 hot water subsystem.
* HWL	Hot Water Subsystem Load	Energy required to satisfy the temperature control demands of the building service hot water system.

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* Primary Performance Factors

SYMBOL	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.
HWSE	Solar Energy to HWS	Amount of solar energy delivered to the HWS.
* HWSFR	HWS Solar Fraction	Portion 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.
RELH	Relative Humidity	Average outdoor relative humidity at the site.
* 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.
SEOP	Operational Incident Solar Energy	Amount of incident solar energy upon the collector array whenever the collector loop is active.

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* Primary Performance Factors

SYMBOL	NAME	DEFINITION
* SEL	Solar Energy to Load Subsystems	Amount of solar energy supplied by the ECSS to all load subsystems.
* SFR	Solar Fraction of System Load	Portion of the system load which was supported by solar energy.
STECH	Change in ECSS Stored Energy	Change in ECSS stored energy during reference 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.
* SYSL	System Load	Energy required to satisfy all desired temperature control demands at the output of all subsystems.
* 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.
* 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.
* TB	Building Temperature	Average temperature of the controlled space of the building.
TCECOP	TCE Coefficient of Performance	Coefficient of performance of the thermodynamic conversion equipment.
TCEI	TCE Thermal Input Energy	Equivalent thermal energy which is supplied as a fuel source to thermodynamic conversion equipment.

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* Primary Performance Factors

SYMBOL	NAME	DEFINITION
TCEL	Thermodynamic Conversion Equipment Load	Controlled energy output of thermodynamic conversion equipment.
TCEOPE	TCE Operating Energy	Amount of energy required to support the operation of thermodynamic conversion equipment which is not intended to appear directly in the load.
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.
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.
* 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.

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* Primary Performance Factors

SYMBOL	NAME	DEFINITION
WDIR	Wind Direction	Average wind direction at the site.
WIND	Wind Velocity	Average wind velocity at the site.

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* Primary Performance Factors

SECTION 2. SOLAR TERMINOLOGY

Absorptivity	The ratio of absorbed radiation by a surface to the total incident radiated energy on that surface.
Active Solar System	A system in which a transfer fluid (liquid or air) is circulated through a solar collector where the collected energy is converted, or transferred, to energy in the medium.
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.
Auxiliary Energy	In solar energy technology, the energy supplied to the heat 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 supplemented in nature but does not have the auxiliary system as an origin, i.e., energy supplied to the space heating load from the external ambient environment by a heat pump. The electric energy input to a heat pump is defined as operating energy.
Auxiliary Energy Subsystem	In solar energy technology the Auxiliary Energy System is the conventional heating and/or cooling equipment used as supplemental or backup to the solar system.
Array	An assembly of a number of collector elements, or panels, into the solar collector for a solar energy system.
Backflow	Reverse flow.
Backflow Preventer	A valve or damper installed to prevent reverse flow.
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.

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 Subsystem	The assembly of components that absorbs incident solar energy and transfers the absorbed thermal energy to a heat transfer fluid.
Concentrating Solar Collector	A solar collector that concentrates the energy from a larger area onto an absorbing element of smaller area.
Conversion Efficiency	Ratio of thermal energy output to solar energy incident on the collector array.
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 average daily temperature is above 65°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.
Drain Down	An arrangement of sensors, valves and actuators to automatically 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 to the system heat transfer fluid expands and contracts to prevent excessive pressure from developing and causing damage.
F-Curve	The collector instantaneous efficiency curve. Used in the "F-curve" procedure for collector analysis (see Instantaneous Efficiency).
Figure of Merit, FMS	A calculated number showing the relative net fraction of the system load supplied from solar energy. $\text{FMS} = \begin{matrix}\text{Solar Energy}\\ \text{Supplied to Load}\end{matrix} - \begin{matrix}\text{Solar System}\\ \text{Operating Energy}\end{matrix}$
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 re-radiated from the panel is trapped within the collector 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 technology, 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 average daily temperature is below 65°F.
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).
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	The solar energy received by a surface.
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 required heating or cooling.
Manifold	The piping that distributes the transport fluid to and from the individual panels of a collector array.

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 (T), and outside ambient temperature (Ta). The operating point is defined as: $\frac{Ti-Ta}{I} \quad \frac{^{\circ}F \times hr. \times sq.\ ft.}{BTU}$
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 that converts energy to useful thermal energy for heating without the use of collector circulating fluid.
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 re-radiates little of it as thermal radiation.

Sensor	A device used to monitor a physical parameter in 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, N_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. 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.

SECTION 3. ABBREVIATIONS

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 Fahrenheit degree. One BTU is equivalent to 2.932 x 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.

APPENDIX D

PERFORMANCE EQUATIONS

WASHINGTON NATURAL GAS

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 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 general computational methods and the specific energy balance equations used for this site.

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

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

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

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

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

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

For a liquid system ΔH is generally given by

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

where 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.

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* See Appendix B.

For an air system ΔH is generally given by

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

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

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

For electrical power, a general example is

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

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

Letter Designations

C = Specific Heat

D = Direction or Position

EE = Electric Energy

EP = Electric Power

F = Fuel Flow Rate

I = Incident Solar Flux (Insolation)

N = Performance Parameter

P = Pressure

PD = Differential Pressure

Q = Thermal Energy

T = Temperature

TD = Differential Temperature

V = Velocity

W = Heat Transport Medium Mass Flow Rate

TI = Time

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

AVERAGE AMBIENT TEMPERATURE (°F)

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

AVERAGE BUILDING TEMPERATURE (°F)

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

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

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

for ± three 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/lb_m-°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

SPECIFIC HEAT - TEMPERATURE FUNCTION FOR WATER

$$\mathrm{HWD} = \mathrm{CP}\ (\mathrm{T150},\ \mathrm{T100}) \times (\mathrm{T150} - \mathrm{T100})$$

specific heat of water evaluated at the temperature specified and multiplied by the temperature difference specified

SOLAR ENERGY COLLECTED PER SQUARE FOOT (BTU)

$$\mathrm{SEC} = \Sigma\ [\mathrm{M100} \times \mathrm{HRF} \times (\mathrm{T150} - \mathrm{T100}]/\mathrm{CLAREA} \times \Delta\tau$$

SOLAR ENERGY TO STORAGE (BTU)

$$\mathrm{STEI} = \Sigma\ [\mathrm{M200} \times \mathrm{HRF} \times (\mathrm{T250} - \mathrm{T200})] \times \Delta\tau$$

measured during collector-to-storage mode

SOLAR ENERGY FROM STORAGE (BTU)

$$\mathrm{STEO} = \Sigma\ [\mathrm{M200} \times \mathrm{HRF} \times (\mathrm{T250} - \mathrm{T200})] \times \Delta\tau$$

measured during space heating modes

AVERAGE TEMPERATURE OF STORAGE (°F)

$$\mathrm{TST} = (1/60) \times \Sigma\ [(\mathrm{T201} + \mathrm{T202} + \mathrm{T203})/3] \times \Delta\tau$$

ECSS OPERATING ENERGY (BTU)

$$\mathrm{CSOPE} = 56.8833 \times \Sigma\ \mathrm{EP100} \times \Delta\tau$$

when system is in the collector-to-storage mode

$$\mathrm{CLOPE} = 56.8833 \times \Sigma\ \mathrm{EP100} \times \Delta\tau$$

when system is in the collector-to-space heating mode

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$$\mathrm{HOPE} = 56.8833 \times \Sigma\ [\mathrm{EP100} + \mathrm{EP400}] \times \Delta\tau$$

when system is in a space heating mode

SPACE HEATING SOLAR-SPECIFIC OPERATING ENERGY (BTU)

$$\mathrm{HOPE1} = 56.8833 \times \Sigma\ \mathrm{EP100} \times \Delta\tau$$

when system is in a space heating mode

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$\mathrm{HSE} = \Sigma\ [\mathrm{M100} \times \mathrm{HRF} \times (\mathrm{T400} - \mathrm{T401})] \times \Delta\tau + \mathrm{STEO}$$

when system is in a space heating mode

SPACE HEATING SUBSYSTEM AUXILIARY FOSSIL FUEL ENERGY (BTU)

$HAF = \Sigma\ FD400 \times 1{,}060 \times \Delta\tau$

where FD400 is F400 fuel consumption

SPACE HEATING SUBSYSTEM AUXILIARY THERMAL ENERGY (BTU)

$HAT = \Sigma\ M600 \times HRF \times (T450 - T400)$

when system is in a space heating mode

SPACE HEATING SUBSYSTEM LOAD (BTU)

$HL = HSE + HAT$

HOT WATER SUBSYSTEM OPERATING ENERGY (BTU)

$HWOPE = 56.8833 \times \Sigma\ EP300 \times \Delta\tau$

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

$HWSE = \Sigma\ M301 \times HWD\ (T352,\ T302) \times \Delta\tau$

SOLAR ENERGY INTO DHW TANK

$HWSE1 = \Sigma\ M300 \times HWD\ (T350,\ T300) \times \Delta\tau$

HOT WATER HEAT EXCHANGER ENERGY, AIRSIDE (BTU)

$HWQIN = \Sigma\ M100 \times HRF \times (T101 - T151) \times \Delta\tau$

HOT WATER SUBSYSTEM AUXILIARY FOSSIL FUEL ENERGY (BTU)

$HWAF = \Sigma\ FD300 \times 1{,}060 \times \Delta\tau$

where FD300 is F300 fuel consumption

HOT WATER SUBSYSTEM AUXILIARY THERMAL ENERGY (BTU)

$HWAT = HWAF \times HWFEFF$

(HWFEFF is heater efficiency = 66%)

HOT WATER SUBSYSTEM LOAD (BTU)

$HWL = \Sigma\ M300 \times HWD\ (T351,\ T300) \times \Delta\tau$

HOT WATER CONSUMPTION (GALLONS)

$HWCSM = \Sigma\ WD300 \times \Delta\tau$

HOT WATER SUBSYSTEM SET TEMPERATURE (°F)

$\text{THW} = \Sigma\ (\text{T351}/60) \times \Delta\tau$, FLOW-WEIGHTED BY M300

HOT WATER SUBSYSTEM MAKE-UP WATER TEMPERATURE (°F)

$\text{TSW} = \Sigma\ (\text{T300}/60) \times \Delta\tau$, FLOW-WEIGHTED BY M300

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$\text{SEA} = \text{CLAREA} \times \text{SE}$

COLLECTED SOLAR ENERGY (BTU)

$\text{SECA} = \text{CLAREA} \times \text{SEC}$

COLLECTOR ARRAY EFFICIENCY

$\text{CAREF} = \text{SECA}/\text{SEA}$

INITIALIZED VALUE USED TO COMPUTE CHANGE IN STORED ENERGY (BTU)

$\text{STECH1} = \text{MASSR} \times \text{CR} \times \text{TST1}$

where MASSR and CR refer to the mass and specific heat of the rocks in the storage bin

CHANGE IN STORED ENERGY (BTU)

$\text{STECH} = \text{STECH1} - \text{STECH1}_p$

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

STORAGE EFFICIENCY

$\text{STEFF} = (\text{STECH} + \text{STEO})/\text{STEI}$

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

$\text{SEL} = \text{CSEO}$

ENERGY DELIVERED FROM ECSS TO SPACE HEATING SUBSYSTEM (BTU)

$\text{CSEO} = \text{HWSE} + \text{HSE}$

ESCC SOLAR CONVERSION EFFICIENCY

$\text{CSCEF} = \text{SEL}/\text{SEA}$

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

HSFR = 100 x HSE/HL

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = -HOPE1

SPACE HEATING SUBSYSTEM FOSSIL FUEL ENERGY SAVINGS (BTU)

HSVF = HSE/0.6

HOT WATER SUBSYSTEM SOLAR FRACTION (PERCENT)

PRELIMINARIES:

TANKV = HWCAP x [RHO(THW) x CP(THW) x THW - RHO(TSW) x CP(TSW) x TSW]

HWTKSE = (HWSFR_P/100) x (TANKV - HWSE1 - HWAT) + HWSE1

HWTKAUX = (1 - HWSFR_P/100) x (TANKV - HWSE1 - HWAT) + HWAT

HWSFR = 100 x HWTKSE/(HWTKSE + HWTKAUX)

HOT WATER SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HWSVE = $-\Sigma$ HWOPE x $\Delta\tau$

HOT WATER SUBSYSTEM FOSSIL ENERGY SAVINGS (BTU)

HWSVF = HWSE1/0.6

SYSTEM LOAD (BTU)

SYSL = HL + HWL

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

SFR = (HWSFR x HL + HWSFR x HWL)/SYSL

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY FOSSIL FUEL ENERGY TO LOADS (BTU)

AXF = HWAF + HAF

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HOPE + HWOPE + CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXF + SECA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HSVE + HWSVE - CSOPE

TOTAL FOSSIL FUEL ENERGY SAVINGS (BTU)

TSVF = HWSVF + HSVF

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXF + 3.33 x SYSOPE)

APPENDIX E

CALCULATION OF PREDICTED VALUES

The modified f-Chart program is used by the NSDN to estimate performance of the solar system. The f-Chart program was developed by the Solar Energy Laboratory, University of Wisconsin-Madison, and was originally intended to be used as a design tool. This program has been modified to use measured weather data and measured subsystem loads and losses in place of average long-term weather data and ASHRAE building heat loss (UA) estimated loads. The results help to determine if the system is performing well.

In addition to the assumptions made for a normal f-Chart analysis, the modified f-Chart assumes that all subsystem loads and losses are reasonable and are the result of good design and insulation practice.

Ref:

(1) Solar Heating Design by the F-Chart Method. William A. Beckman, Sanford A. Klein, John A. Duffie, Wiley Interscience, N.Y. (1977)

(2) F-Chart User's Manual. EES Report 49-3, SERI, Department of Energy, (June 1978)

SYSTEM PERFORMANCE SUMMARY (f-CHART)*
WASHINGTON NATURAL GAS
NOVEMBER 1979, FEBRUARY AND APRIL 1980

(All values in million BTU, unless otherwise indicated)

MONTH	ESFR (%)	ASFR (%)	LOAD*	LOSS	STECH	ESECA	ASECA*	ESEU	ASEU
NOV	7	11	8.160	0.750	-0.260	0.818	1.418	0.535	0.760
FEB	23	26	6.300	0.980	0.230	2.214	3.464	1.441	1.500
APR	51	38	4.160	1.740	0.270	3.749	4.611	2.115	1.490
TOTAL	-	-	18.620	3.470	0.240	6.781	9.493	4.091	3.750
AVERAGE	22	22	6.207	1.157	0.080	2.260	3.164	1.364	1.250

*These inputs are slightly different from actual values.

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*See next page for glossary of f-Chart terms.

GLOSSARY OF f-CHART TERMS

ESFR - Expected (predicted) solar fraction

ASFR - Actual (measured) solar fraction

LOAD - Measured total system load

LOSS - Total system losses (transport and storage)

STECH - Change in stored energy

ESECA - Expected (predicted) solar energy collected

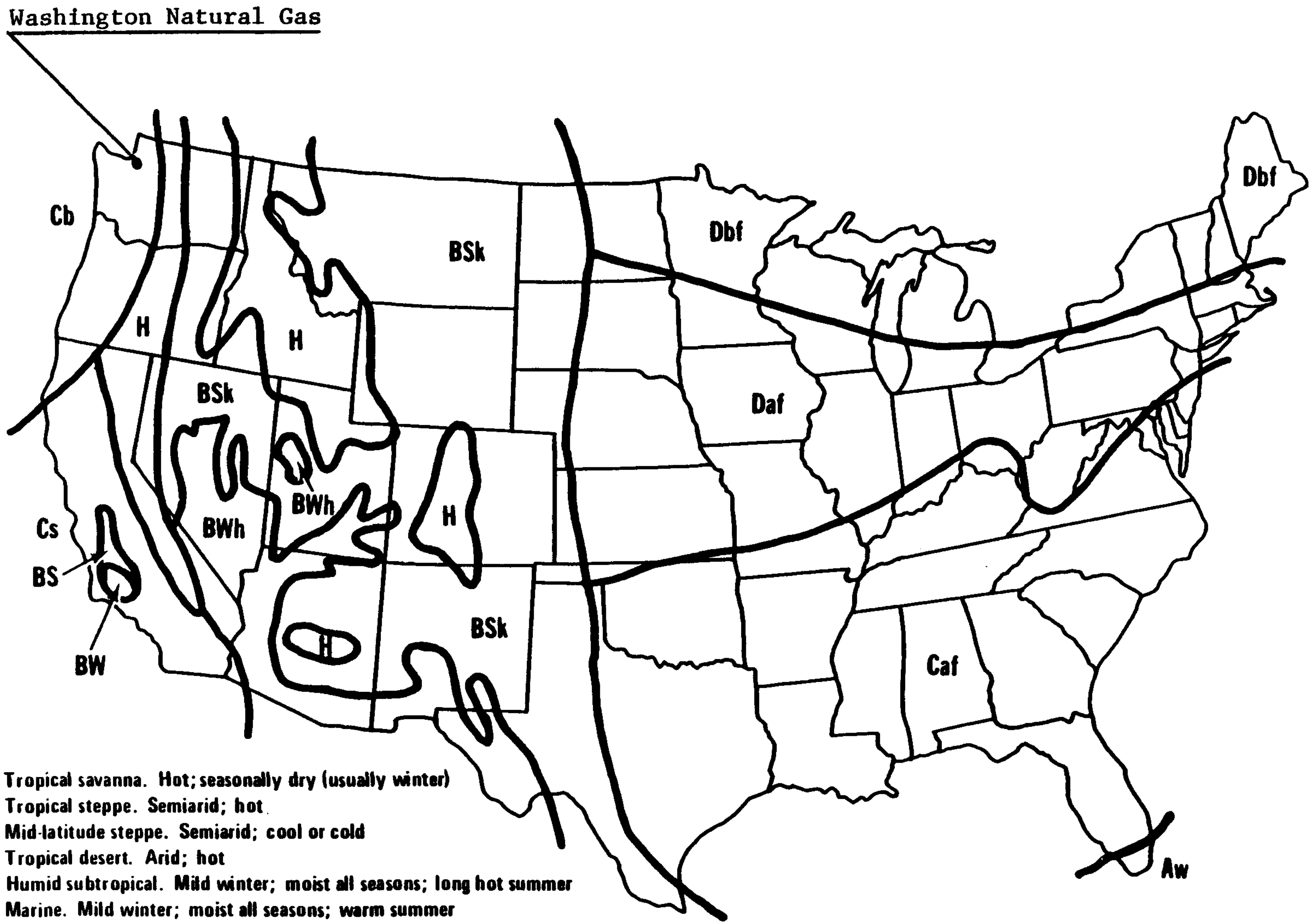
ASECA - Actual (measured) solar energy collected

ESFU - Expected (predicted) solar energy used

ASEU - Actual (measured) solar energy used

APPENDIX F

METEOROLOGICAL CONDITIONS



KEY

Aw	Tropical savanna. Hot; seasonally dry (usually winter)
BS	Tropical steppe. Semiarid; hot
BSk	Mid-latitude steppe. Semiarid; cool or cold
BWh	Tropical desert. Arid; hot
Caf	Humid subtropical. Mild winter; moist all seasons; long hot summer
Cb	Marine. Mild winter; moist all seasons; warm summer
Cs	Coastal Mediterranean. Mild winter; dry summer; short warm summer
Daf	Humid continental. Severe winter; moist all seasons; long, hot summer
Dbf	Humid continental. Severe winter; moist all seasons; short warm summer
H	Undifferentiated highland climates

Trewartha, G.T. The Earth's Problem Climates. University Wisconsin Press, Madison, WI, 1961.

Figure F-1. Meteorological Map of the United States Showing Location of Washington Natural Gas

WASHINGTON NATURAL GAS LONG-TERM WEATHER DATA

COLLECTOR TILT: 57 DEGREES
LATITUDE: 47 DEGREES

LOCATION: KIRKLAND, WASHINGTON
COLLECTOR AZIMUTH: 0 DEGREES

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
NOV	1,038	339	0.32690	1.807	613	612	0	45
FEB	1,409	494	0.35074	1.560	771	636	0	42
APR	2,821	1,294	0.45877	0.996	1,290	489	0	49

LEGEND:

HOBAR - Monthly average daily extraterrestrial radiation on a horizontal surface (ideal) in BTU/day-ft^2.

HBAR - Monthly average daily radiation (modeled from SOLMET) in BTU/day-ft^2.

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 x HBAR) in BTU/day-ft^2.

HDD - Number of heating degree-days per month.

CDD - Number of cooling degree-days per month.

TBAR - Average ambient temperature in degrees Fahrenheit.

MONTHLY REPORT: WASHINGTON NATURAL GAS
NOVEMBER 1979
ENVIRONMENTAL SUMMARY

DAY OF MONTH (NBS ID)	TOTAL INSOLATION BTU/SQ. FT (Q001)	AMBIENT TEMPERATURE DEG F (N113)	DAYTIME AMBIENT TEMP DEG F
1	1618	45	53
2	156	51	53
3	118	50	52
4	246	51	53
5	182	50	52
6	1233	50	55
7	1540	49	54
8	777	42	46
9	508	42	43
10	86	44	47
11	753	40	42
12	848	40	42
13	901	40	42
14	815	42	44
15	542	45	47
16	87	49	49
17	247	47	52
18	173	43	46
19	896	44	47
20	857	40	42
21	954	44	50
22	16	44	43
23	226	43	45
24	22	40	40
25	85	41	43
26	396	38	40
27	1152	35	39
28	997	42	48
29	94	43	47
30	192	42	44
SUM	16716	-	-
AVG	557	44	47

MONTHLY REPORT: WASHINGTON NATURAL GAS
FEBRUARY 1980
ENVIRONMENTAL SUMMARY

DAY OF MONTH (NBS ID)	TOTAL INSOLATION BTU/SQ. FT (Q001)	AMBIENT TEMPERATURE DEG F (N113)	DAYTIME AMBIENT TEMP DEG F
1	*	*	*
2	*	*	*
3	*	*	*
4	*	*	*
5	*	*	*
6	*	*	*
7	*	*	*
8	643	41	42
9	782	39	*
10	1605	37	41
11	*	*	*
12	*	*	*
13	*	*	*
14	*	*	*
15	*	*	*
16	*	*	*
17	*	*	*
18	*	*	*
19	*	*	*
20	*	*	*
21	1513	39	44
22	1311	39	*
23	1638	45	50
24	271	52	52
25	284	50	54
26	57	51	53
27	53	53	55
28	599	49	52
29	289	49	51
SUM	22,613E	-	-
AVG	754E	45E	49E

* DENOTES UNAVAILABLE DATA.
E DENOTES ESTIMATED VALUE.

Valid data was available for about two and one-half months of the heating season, and those months are nonconsecutive. Estimates were made to a full month's data based on the 12 days of available February data. It is important to note that all February 1980 values in this report include or are based on these estimates.

Based on the limited amount of data available, it is difficult to draw conclusions about the entire heating season, which runs from November through April. However, because the data available does cover a wide variety of weather conditions and systems responses, and provides a look at the system problems encountered this season, this report is useful.

One problem with data which has been consistently baffling is that the fuel meters maintained by the NSDN and the grantee's own fuel meter apparently do not agree. The Washington Natural Gas Company has had all on-site gas meters checked and all were verified accurate in 1980. Possible reasons for the discrepancy in meter readings include: the temperature difference in the environments of the meters - the grantee's is outside, the NSDN's inside; averaging of results on the part of the grantee; possible undiscovered NSDN software errors in converting sensor readings to consumptions.

APPENDIX H

CONVERSION FACTORS

Energy Conversion Factors[1]

Fuel Type	Energy Content	Fuel Source Conversion Factor
Distillate fuel oil[2]	138,690 BTU/gallon	7.21×10^{-6} gallon/BTU
Residual fuel oil[3]	149,690 BTU/gallon	6.68×10^{-6} gallon/BTU
Kerosene	135,000 BTU/gallon	7.41×10^{-6} gallon/BTU
Propane	91,500 BTU/gallon	10.93×10^{-6} gallon/BTU
Natural gas	1,021 BTU/cubic feet	979.4×10^{-6} cubic feet/BTU
Electricity	3,413 BTU/kilowatt-hour	292.8×10^{-6} kwh/BTU

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[1] Source information is from the Dept. of Energy "Monthly Energy Review" FEB 1980

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

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

APPENDIX I

SENSOR TECHNOLOGY

Temperature Sensors

Temperatures are measured by a Minco Products S53P platinum Resistance Temperature Detector (RTD). Because the resistance of platinum wire varies as a function of temperature, measurement of the resistance of a calibrated length of platinum wire can be used to accurately determine the temperature of the wire. This is the principle of the platinum RTD which utilizes a tiny coil of platinum wire encased in a copper-tipped probe to measure temperature. The probes are designed to have a normal resistance of 100 Ohms at 32°F.

Ambient temperature sensors are housed in a WeatherMeasure Radiation Shield in order to protect the probe from solar radiation. Care is taken to locate the sensor away from extraneous heat sources which could produce erroneous temperature readings. Temperature probes mounted in ducts or pipes are installed in stainless steel thermowells for physical protection of the sensor and to allow easy removal and replacement of the sensors. A thermally conductive grease is used between the probe and the thermowell to assure faster temperature response.

The RTDs are connected in a Wheatstone bridge arrangement to yield an output signal of 0-100 millivolts, which is measured by the SDAS. Different resistance values are used in the bridge, depending on the temperature range the sensor must measure. A third wire is brought out from the sensor and connected into the bridge to compensate for the resistance of the lead wires between the sensor and the SDAS.

The RTDs are individually calibrated by the manufacturer to National Bureau of Standards traceable standards. In addition, a five-point transmission system calibration check is done at the site to compensate for any deviation of the measurement system from nominal values.

The data-processing software takes these checks and calibrations into account, using a third-order polynomial curve fit to relate SDAS output to temperature.

Wind Sensor

Wind speed and direction are measured by a Model W101-P-DC/540 (or W102-P-DC/540) sensor made by the WeatherMeasure Corporation. This sensor is rugged, reliable and accurate and will withstand severe environments such as icing and hurricane winds.

Wind speed is measured by a four-bladed propeller vehicle coupled to a DC generator. The balanced propeller is fabricated from a special low-density, fiberglass-reinforced plastic to yield maximum sensitivity and strength. The DC generator has excellent linearity but somewhat higher threshold due to brush friction.

Dual-wiper, precious-metal slip rings are used to connect the wind speed generator signal (15 Volts DC at 100 miles per hour) to the data transmission lines. These generally provide trouble-free use for several years.

Wind direction is measured by means of a dual-wiper 1000-Ohm long-life conductive plastic potentiometer housed in the base of the sensor (0-540°). It is attached to the stainless steel shaft which supports and rotates with the upper body assembly.

The potentiometer is of high commercial grade and has sealed bearings. The conductive plastic resistance element has infinite resolution and a lifetime about 10 times that of wire-wound potentiometers. The base is of aluminum, and corrosion-resistant materials are used in the construction.

Humidity Sensors

Relative humidity is measured by a WeatherMeasure Corporation Model HM111-P/HM14-P sensor. This measurement is of particular importance in solar cooling systems.

This solid-state sensor measures relative humidity over the full range of 0-100%. Response of the sensing element is linear within approximately 1%, from 0-80% relative humidity, with small hysteresis and negligible temperature dependence.

The sensor is based upon the capacitance change of a polymer thin-film capacitor. A one-micron-thick dielectric polymer layer absorbs water molecules through a thin metal electrode and causes capacitance change proportional to relative humidity. The thin polymer layer reacts very quickly and, therefore, the response time is very short (one second to 90% humidity change at 68°F).

The polymer material is resistant to most chemicals. Because the sensor response is based on "bulk" effect, under normal conditions dust and dirt do not easily influence its operation. For use outdoors, a sintered filter is used because sulphur dioxide absorbed on small particles can corrode the thin film electrodes of the sensor. The smaller the pore size of the filter, the greater the protection. The response time, however, is increased.

The sensor is mounted in a small probe which contains all the electronics necessary to provide a millivolt output. The output of the probe electronics is linear from 0-100% relative humidity. Because the capacitance change of the sensor is sensitive only to ambient water vapor, temperature compensation is not required in most situations.

Insolation Sensors

Eppley pyranometers and shadowband pyranometers are used to measure the amount of radiant energy incident on a surface. A standard pyranometer measures the total amount of solar energy available, including both the direct beam component and the diffuse component, while the shadowband instrument is designed to measure the diffuse component only. The instruments are calibrated in the horizontal position, with an Eppley thermopile used as the signal generator of the sensor. The heating of the thermopile by the radiation of the sun generates the signal, with the response being linear over the operating range. Measurements are in BTU/ft^2-hr.

The addition of a shadowband to a pyranometer enables the instrument to record only the diffuse portion of the sunlight by shielding the sensor from the direct rays of the sun (the beam component). The amount of beam radiation available is readily calculated by subtracting the diffuse radiation measurement from the total radiation measured by the unshaded standard pyranometer. This beam radiation measurement is useful when working with focusing solar collectors. When using the shadowband pyranometer, the accuracy of its measurement depends on the correct adjustment of the shadowband to be certain that the sensor is shielded from the direct rays of the sun.

The pyranometer includes a circular multijunction thermopile of the wire-wound type. The thermopile has the advantage of withstanding some mechanical vibration and shock. The receiver is circular, and coated with Parsons black lacquer. The instrument has a pair of removable precision ground and polished hemispheres of Schott optical glass. It also has a spirit level and a desiccator that can be readily inspected. The clear glass is transparent from a wavelength of about 285 to 2,800 nanometers. The temperature dependence is ±1% over the range of -4°F to 104°F. It has a response time of one second and a linearity of ±5% over the range of the instrument.

Flow Sensors

The Ramapo flow meter is an accurate and sensitive liquid flow rate measuring device. The dynamic force of fluid flow, or velocity head of the approaching stream, is sensed as a drag force on a target (disc) suspended in the flow stream. This force is transmitted via a lever rod and flexure tube to an externally bonded, four active arm strain gauge bridge. This strain gauge bridge circuit translates the mechanical stress due to the sensor (target) drag into a directly proportional electrical output. Translation is linear, with infinite resolution, and is hysteresis free. The drag force itself is usually proportional to the flow rate squared. The electrical output is unaffected by variations in fluid temperature or static pressure head, within the stated limitations of the unit.

Kurz Models 430 and 435 are general purpose, bench-top or permanent installation, velocity and mass flow measurement systems operated on line voltage. The output voltage, suitable for recording and other purposes is 0 to 5 vdc for several choices of air velocity. Model 430 features low-speed sensitivity down to a few feet per minute. The nonlinear logarithmic output voltage allows a rangeability of at least 100:1. Model 435 has a linear 0-5 vdc output voltage suitable for display, recording and totalizing.

Models 430 and 435 are used as an insertion probe in ducts and pipes for the measurement of velocity or total mass flow rate of air flow in a variety of applications.

The basic sensing element of Models 430 and 435 is the "DuraFlo" probe. The "DuraFlo" probe consists of two integral sensors: a velocity sensor and a temperature sensor. The velocity sensor is a constant-temperature thermal anemometer which measures "standard" velocity (referenced to 70°F and 760 mm Hg), or mass flow, by sensing the cooling effect of the moving flowstream as it passes over the heated sensor. The sensor is heated electrically by the control circuitry in the electronics package. The velocity sensor is breakage resistant and insensitive to particulate contamination. The temperature sensor compensates for temperature variations over a wide range. The probe is used directly to measure air velocity in open spaces, ducts and supply and return openings.

Power Sensors

A major component of the wattmeter is a concentrating magnetic core (usually a toroid). The conductor carrying current to the load is passed through the window (eye) of the magnetic core one or more times. The magnetic field surrounding the conductor (load-carrying wire) is instantaneously proportional to the current flowing in the conductor. This field is intercepted by the magnetic core, producing a magnetic flux which is also instantaneously proportional to the current flowing in the conductor. A Hall effect transducer is cemented into a thin slot milled through the concentrating magnetic core.

In this position it intercepts nearly all of the magnetic flux present in the core. Two of the transducer's terminals provide a full scale output of 50MVDC. The remaining two terminals are referred to as a control input. The output of the Hall transducer is not only proportional to the magnetic flux passing through it but also to any EMF which appears across its control terminals. The load voltage is applied to the transducer's control terminals.

The resultant measurements of the wattmeter are summarized below:

1. Output is directly proportional to the flux in the magnetic core which in turn is directly proportional to the load current (I).

2. Output is directly proportional to the load voltage (E).

3. Final output is directly proportional to the vector product of E, I, and cos ϕ (power factor angle). This output is read into the SDAS as an electrical power in watts.

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