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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION UPDATE

WOOD ROAD SCHOOL
Ballston Spa, New York
October 1982 through April 1983
DHW SH

U.S. DEPARTMENT OF ENERGY
NATIONAL SOLAR DATA PROGRAM

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WOOD ROAD SCHOOL
BALLSTON SPA, NEW YORK
SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION
UPDATE
OCTOBER 1982 THROUGH APRIL 1983

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FOREWORD

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

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

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

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

WOOD ROAD SCHOOL

WOOD ROAD SCHOOL

The Wood Road School Solar Project of the Ballston Spa Central School District is a 216,000-square-foot (136,510 square feet of solar conditioned space) combined elementary and middle school located in Ballston Spa, New York. The solar system supplies energy to the Space Heating (SH) and Domestic Hot Water (DHW) subsystems. The active solar energy system is equipped with:

Collector: 15,389 square feet of Vulcan Model CC-1F/G flat-plate collector panels (591 panels), plus
6,650 square feet of Novan Model 98SC flat-plate collector panels (270 panels)

Storage: Two 15,000-gallon storage tanks located adjacent to the school complex

Auxiliary: Electric resistance strip heaters

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SECTION 1

SOLAR SYSTEM PERFORMANCE

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

Solar Fraction (SFR) ¹	-16% E
Solar Savings Ratio (SSR) ²	0.12 E
Conventional Fuel Savings (TSVE) ³	85,200 kwh E
System Performance Factor (SYSPF) ⁴	0.34 E
Solar System COP (COP) ⁵	4.6 E

Seasonal Energy Requirements
October 1982 through April 1983
(Million BTU)

	<u>Subsystem Load</u>	<u>Solar Contribution</u>	<u>% Solar</u>
Heating	2,140 E	332 E	15 E
Hot Water	220 E	41.2 E	19 E

Environmental Data

	<u>Measured Average</u>	<u>Long-Term Average</u>
Outdoor Temperature	36°F	35°F
Heating Degree Days (Total)	6,051	6,430
Daily Incident Solar Energy	1,032 BTU/ft ²	988 BTU/ft ²

$$1. \text{ Solar Fraction} = \frac{\text{Solar Contribution to Loads (SEL)}}{\text{Total Load (EHL + HWL)}} \times 100$$

$$2. \text{ Solar Savings Ratio} = \frac{\text{Solar Contribution to Loads (SEL)} - \text{Solar-Unique Operating Energy (SYSOPEI)}}{\text{Total Load (EHL + HWL)}}$$

$$3. \text{ Conventional Fuel Savings} = \text{Savings in BTU (TSVE)} \times 292.8 \times 10^{-6} \text{ kwh/BTU}$$

$$4. \text{ System Performance Factor} = \frac{\text{System Load (EHL + HWL)}}{3.33 \times [\text{Auxiliary Electric Energy (AXE)} + \text{Solar-Unique Operating Energy (SYSOPEI)}]}$$

$$5. \text{ Solar System COP} = \frac{\text{Solar Energy Used (SEL)}}{\text{Solar-Unique Operating Energy (SYSOPEI)}}$$

E Denotes estimated value.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

1.1 SUMMARY AND CONCLUSIONS

This report is the second in a series of performance evaluation reports on the Wood Road School Solar Project, located in Ballston Spa, New York. Readers are referred to the following document to aid in their understanding of this report:

*Solar Energy System Performance Evaluation, Wood Road School,
November 1981 through April 1982, SOLAR/2125-82/14
(Reference 1)

This second report contains updated performance data on the Project for the heating season beginning in October 1982 and lasting through April 1983.

The Wood Road School Solar Project of the Ballston Spa Central School District is a cooperative experimental solar system designed to provide hot water and heating contributions to the Wood Road Elementary School in Ballston Spa, New York.

The Project was funded by the School District, the New York State Department of Education, the New York State Energy Research and Development Authority, and the U.S. Department of Energy under the Solar Heating and Cooling Demonstration Program PON-2 cycle. Monitoring of the performance of the system has been undertaken through a joint effort by the Niagara-Mohawk Electric Power Company (and their subcontractor, Trautman Associates) and the Department of Energy through Vitro Laboratories. This report represents the compilation of the thermal performance data on the Project. The data in this report supersedes data from monthly performance analyses.

Several basic methods of assessing the thermal performance of the solar system at the Wood Road School are used in this report. Each of these areas is important; however, summing up the overall system performance must account for many variables. Any one of these factors, taken alone, may or may not represent an accurate measure of performance. Taken as a group, however, these factors begin to indicate the general performance trends at the site. These areas include:

- A comparison of design vs. actual system solar fraction (Section 1.1)
- Net energy savings in BTU and kwh (Sections 1.1 and 3.2)
- Percentage of incident solar energy utilized (Section 1.2)
- Percentage of collected solar energy utilized (Section 1.2)
- Building loads analysis (Sections 1.1 and 2.3)

* Copies of this report are available from the U.S. Department of Energy, Technical Information Center, P.O. Box 62, Oak Ridge, TN 37830.

- System thermal losses (Sections 1.1, 1.2, and 2.2)
- Solar system Coefficient of Performance (COP) (Sections 1.1 and 3.1)
- Subsystem thermal performance (Section 2)
- Weather conditions (Section 3.3)

The thermal performance of the solar system over the seven-month heating season is presented in Table 1, and a bar chart showing solar contribution, auxiliary electric energy used, and operating energy is shown in Figure 1.

Table 1. SOLAR SYSTEM THERMAL PERFORMANCE

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU, unless otherwise indicated)

MONTH	SOLAR ENERGY COLLECTED (SECA)	SYSTEM LOAD (SYSL)	SOLAR ENERGY USED (SEL)	AUXILIARY ENERGY ELECTRICAL (AXE)	OPERATING ENERGY (SYSOPEI)	ENERGY SAVINGS ELECTRICAL (TSVE)	SOLAR FRACTION (?) (SFR)
OCT	127	182 E	24.0 E	158	6.40	17.6 E	13 E
NOV	104 E	284 E	43.4 E	240	13.9	29.5 E	15 E
DEC	60.0 E	361 E	27.8 E	334	10.7	17.1 E	8 E
JAN	76.9	451 E	57.1 E	394	14.2	42.9 E	13 E
FEB	118	316 E	80.3 E	236	13.8	66.5 E	25 E
MAR	76.9	423 E	54.3 E	368	8.70	45.5 E	13 E
APR	123	345 E	86.3 E	259	14.4	71.9 E	25 E
TOTAL	686 E	2,360 E	373 E	1,990	82.1	291 E	-
AVERAGE	98.0 E	337 E	53.3 E	284	11.7	41.6 E	16 E

E Denotes estimated value.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

As seen in Table 1 and in Figure 1, the solar fraction was an estimated 16% of the 2,360 million BTU system load over the seven-month season. The solar system did not perform as well in 1983 as in 1982. Taking similar months with similar loads, the estimated solar fraction during the spring of 1983 was lower than the solar fraction reported for the spring of 1982.

The total solar contribution to the hot water and heating subsystems was 373 million BTU, which was comprised of an estimated 41.2 million BTU transferred to the hot water subsystem, and an estimated 332 million BTU delivered to the heating subsystem. This solar contribution represents eight percent of the total available radiation at the collector array, or 54% of the collected solar energy.

OPERATING ENERGY FOR THE SYSTEM IS CONSIDERED A SYSTEM PENALTY AND IS PLOTTED AS A NEGATIVE VALUE BELOW THE ORIGIN.

Figure 1. Solar System Thermal Performance
Wood Road School
October 1982 through April 1983

These values are close to those measured the previous year. For example, 54% of the collected energy was utilized this year, while 56% was used during 1981-1982. Also, 10% of the incident energy was used in the previous monitoring period, while eight percent was used this year. Within the limits of uncertainty, it appears that the overall conversion efficiency did drop slightly since the previous year, as the eight percent figure indicates. Possible reasons for the lowered performance will be discussed in later sections.

The solar fraction averaged an estimated 16% from October 1982 through April 1983. A total of 1,990 million BTU (583,000 kwh) of auxiliary electric power was consumed by the auxiliary systems at the school, comprised of resistance electric heating elements and fans in the Heating, Ventilating, and Air-Conditioning (HVAC) system and three electric resistance hot water heaters.

The percentage of the auxiliary use at the school which is attributed to the operation of the air handlers is not known, however, the energy used by the fans is assumed to meet a part of the heat load, since frictional heating of the air due to fan operation and motor losses provides some heat to the building.

The energy savings at the Wood Road School were 85,200 kwh estimated over the seven-month period. These savings are equivalent to \$5,112, at an average estimated cost of \$0.06 per kwh (excluding demand charges and other rate structures). The later months showed savings of nearly \$1,200 per month. This figure is based on actual solar energy delivered, minus the system operating energy.

Savings appeared lower this year. Based on a 22,039-square-foot collector area (collector gross area of 861 panels), the savings were approximately 62 BTU/ft²-day. This is less than one-third of the NSDN average heating system savings.

A comparison of 16 NSDN sites (Reference 14) indicates that a typical average value of net savings per square foot per day for flat-plate liquid collector systems was 235 BTU/ft²-day. This value is calculated using net total savings in million BTU divided by the collector area in square feet and the total number of days of measured data. It may be seen that the Wood Road School was in the lower half of the distribution of average savings values for these sites. Additionally, when summer months are figured into the savings, the savings per day of "installed system time" are even lower. All heating and Domestic Hot Water (DHW) systems suffer from severely reduced loading in the summer months, and the Wood Road School is no exception.

With regard to net dollar or thermal savings, bear in mind that this figure includes costs due to operational energy requirements only, but not operational, repair and maintenance costs, interest charges, and other nonquantified cost figures. One must conclude that net dollar savings per square foot of collector system installed at the school are, at present, very low (if positive at all).

Figure 2 is an energy flow diagram which graphically depicts the flow of energy through the system and through the various subsystems at the Wood Road School. The flow diagram is a useful way of looking at the performance of the system, since each block must "balance" or account for the energy input, losses, and energy output.

An estimated total of 107 million BTU, or nearly 16% of the collected solar energy, was lost by the storage-to-load distribution piping, which is partially buried and partially exposed to the ambient air. The condition and type of pipe insulation is unknown; therefore, this large percentage of lost energy is difficult to validate. It appears that high thermal losses are one of the limiting factors to better thermal performance. Pipe losses were reduced compared to the previous year's values.

Storage losses were 199 million BTU or 28% of the collected solar energy. Actual delivered solar energy was 54% of the 686 million BTU of energy collected by the solar collectors, which was nearly the same the previous year.

Figure 2. Energy Flow Diagram for Wood Road School
October 1982 through April 1983
(Figures in million BTU)

Figure 3 is a plot of measured monthly solar fraction vs. the predicted monthly solar fraction. Note that the predicted solar fraction is over 50% in all months, yet the highest fraction achieved was 25%. There also seems to be little change in solar contribution with an increase or decrease in load.

Figure 3. Actual vs. Predicted Solar Fraction
Wood Road School
October 1982 through April 1983

There are several apparent reasons for the disparity between the design performance levels shown in Figure 3 and the actual performance of the site. The design values were calculated before the system was built as part of the technical proposal for the U.S. Department of Energy, for a site having 20,000 square feet of flat-plate solar collectors (Reference 15).

Historical data on the building (Reference 15) indicates that the loads have been on the order of 11 to 14 BTU/ft²-Heating Degree-Day (HDD) based on total energy consumed at the school during the mid-1970s. This year, the solar conditioned portion of the building (136,510 square feet) consumed a total of 2,590 million BTU, with a 6,051 heating degree-day season, for a heating seasonal energy consumption rate of 3.14 BTU/ft²-HDD. The conservation measures taken at the school since the mid-1970s appear to have had a dramatic effect as far as reduction of total power consumption. Based on total power consumption at the complex (see Table 7, Total Power Consumption at the Wood Road School Complex) of 4,330 million BTU, and an area of 216,000 square feet, the total energy consumed over the seven months was 3.31 BTU/ft²-HDD. These values do not include summer energy consumption, so they are not directly comparable to the figures from Reference 15.

The solar system, based on the measured data, appears to be saving energy; however, most of the reduction in demand from the 1975-1976 period is probably due to conservation retrofits. The solar system, however, has the potential for increased savings. This will be explained later.

Some of the reasons why performance was below design expectations are:

- System controls and collector operational sequences
- Solar utilization and displacement of auxiliary energy
- Building heat exchanger capacity
- System losses - storage, piping, and transport
- Collector efficiency - performance values for the Vulcan collectors are low
- Weather conditions

Briefly, each of these areas is described in the following paragraphs.

- System controls and collector operational sequences

The control system at the school apparently does not prioritize the use of solar energy. There were numerous times when energy was available in the solar tank, and the solar pumps were activated, yet the net temperature drop across the building was consistently lower than expected. (See Section 2.3, Space Heating Subsystem.)

- Solar utilization and displacement of auxiliary energy

Control systems and existing equipment at retrofitted sites often do not allow displacement of auxiliary consumption. There were recurring instances when solar energy was transferred to the building and the auxiliary electric consumption rate appeared to be nearly the same as on days when no solar energy was transferred. (See Section 2.3, Space Heating Subsystem.) The building load increased and no apparent reduction in power use was the result.

- Building heat exchanger capacity

The overall temperature drop across the terminal equipment at the school was below the design value of 20°F. This drop reduced solar utilization during evening hours particularly. In addition, during November and December, the space heat loop flow was reduced by 25% in an attempt to raise the temperature drop across the building. Lower solar contribution was a result of this experiment. (See Section 2.3, Space Heating Subsystem.)

- System losses - storage, piping, and transport

Nearly 44% of the energy entering the storage tank from the collectors (and additional energy not accounted for in the collector loop piping) was lost due to thermal heat loss. Estimated totals of 199 million BTU were storage losses and 107 million BTU were pipe loop losses. The storage tanks could have been placed in a configuration which would have reduced these losses significantly. In fact, this problem is not unique to the Wood Road School - other large sites have shown significant loss rates from exterior storage tanks and buried pipes. (See Section 2.2, Storage Subsystem.)

- Collector efficiency

The solar system at the Wood Road School had an estimated operational collection efficiency of 31% over the seven-month season. The estimated overall efficiency was 14%, which is relatively poor for collectors of the type used at the school. If the overall collection efficiency were closer to design performance, then more energy would have been available for use. (See Section 2.1, Energy Collection Subsystem, for further discussion of collector performance.) The single-glazed Vulcan array has performance figures which are comparatively low, primarily due to threshold losses.

- Weather conditions

The system design information provided (see Section 2.3, Table 6) indicates the expected heating degree-days, 4,936. Actual data shows the heating load based on degree-days to be higher. In addition, available insolation was expected to be 797 BTU/ft²-day in the horizontal plane. Actual measurements and interpolated data from the nearby National Weather Service insolation measurement stations indicate that this expectance is too high, by about 10%. NSDN long-term data (Reference 1) shows an average long-term insolation closer to 728 BTU/ft²-day.

1.2 SOLAR ENERGY UTILIZATION

The bar chart in Figure 4 shows the various steps in collection, storage, and distribution of the available solar radiation. Each step from left to right shows the process of energy conversion which provides the solar contributions to the load.

Consider the bar labeled "Threshold Losses." All solar sites exhibit some insolation threshold below which the operation of the collector pump(s) is unjustified due to excessive power consumption, losses, etc.

Figure 4. Solar Energy Use
Wood Road School
October 1982 through April 1983

Threshold losses are due to periods of low insolation, at the beginning and end of the day, during which the collector plate temperature is too low to allow the collector pump to operate. The threshold losses were 54% of the available insolation.

These threshold losses increased from the previous season's value of 35%. Therefore, this is an area which deserves some attention.

The collector inefficiency refers to solar energy which was available to be collected while the pump was operating but was not collected due to reflective, radiative, and convective losses to the environment. Collector inefficiency also includes pipe losses, since the energy to the tanks is measured at the tanks' inlet. These losses amounted to 32% of the available energy.

Already, one can see that, before any of the available solar energy even reaches the storage tank, a total of 86% of the available insolation of 4,820 million BTU has been lost due to a variety of reasons, some of which may be uncorrectable.

Once the energy is collected, then system thermal losses occur. On the scale of the chart, note that the storage and transport losses are relatively small compared to the previously mentioned collection loss figures. While the values are small percentages of total insolation, storage and transport losses amounted to 44% of the collected energy, while totaling only six percent of the available insolation.

The operation of the various subsystems is presented in detail in the next sections.

SECTION 2

SUBSYSTEM PERFORMANCE

2.1 ENERGY COLLECTION SUBSYSTEM

The solar collector array at the Wood Road School consists of both Novan Model 98SC and Vulcan Model CC-1F/G flat-plate solar collectors, rack-mounted in a field adjacent to the school building.

Performance of the 22,039-square-foot array is discussed in this section.

Table 2 is a compilation of the results of the analysis of the collectors showing total incident radiation, operational incident radiation, collection efficiency, and operating energy requirements as well as the daytime ambient temperatures.

Table 2. COLLECTION SUBSYSTEM PERFORMANCE

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU, unless otherwise indicated)

MONTH	INCIDENT SOLAR RADIATION (SEA)	COLLECTED SOLAR ENERGY (SECA)	COLLECTION SUBSYSTEM EFFICIENCY (%) (CLEF)	OPERATIONAL INCIDENT ENERGY (SEOP)	COLLECTOR ARRAY OPERATIONAL EFFICIENCY (%) (CLEPOP)	ECSS		ENERGY REJECTION FROM STORAGE (CSRJE)	TEMPERATURE (°F) (TDA)
						PUMP OPERATING ENERGY (CSOPE)	AUXILIARY HEAT TRACE (CSAUX)		
OCT	1,040	127	12	368	35	1.40	0.00	2.06	63
NOV	548	104 E	18 E	296	35 E	1.24	0.09	2.94	47
DEC	443	60.0 E	14 E	195	31 E	0.85	2.98	1	33
JAN	645	76.9	12	357	22	1.36	3.02	5.62	27
FEB	697	118	17	398	30	1.38	1.86	2.92	35
MAR	739	76.9	10	238	32	0.76	1.86	2.26	41
APR	711	123	17	374	33	1.63	0.80	2.34	50
TOTAL	4,820	686 E	-	2,230	-	8.62	10.6	18.1 *	-
AVERAGE	688	98.0 E	14 E	318	31 E	1.73	1.52	3.02*	42

E Denotes estimated value.

! Denotes invalid data.

* Six-month total and average

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

A total of 4,820 million BTU was available at the surface of the collector array, based on actual measured insolation multiplied by the actual measured gross area of the array. (The panels were measured and counted to determine the collector area.) Of this 4,820 million BTU, a total of 2,230 million BTU or 46% was incident during the operation of the collector pump. This value for operational incident energy is lower than usually experienced at other systems.

Gross collection efficiency or overall efficiency was an estimated 14%, based on the 686 million BTU which entered the storage tanks. This efficiency was about three percentage points lower than the 17% efficiency measured the previous season.

Operational collection efficiency was estimated to be 31% over the seven-month period, which was actually an improvement of five percentage points over the previous season.

Indications are that:

- The collector controls could be better adjusted to operate the collector pump during more of the periods having insolation available, based on overall efficiency.
- The collector array performance has not degraded since the previous year and has improved slightly, based on operational efficiency.

Two months of data were actually not available during the season due to a sensor failure. The temperature probe which measures the outlet temperature failed in November and was replaced at the beginning of January. Projected values were therefore included for collector output during these two months. The values were estimated using knowledge of the collector operating curves and the values measured for daily insolation, as well as collector pump operation.

The collector pump used a total of 8.62 million BTU, equivalent to 2,520 kwh. On a per-square-foot basis, the pump operating energy was quite low, about 0.54 W/ft²-day.

The auxiliary freeze protection mechanism for this system consists of heat trace cables attached to the manifolds of the drainback array. These cables actually consumed more energy than the collector pump. A total of 10.6 million BTU, or 3,100 kwh, was expended to prevent manifold and distribution pipe freezing.

In order to assess energy savings at the site, both the heat trace and pump power requirements were summed to provide a total operating energy requirement of 19.2 million BTU.

Collector operating curves, by month (with the exception of November), are shown in Figures 5a through 5f.

The Novan solar collectors are a higher performance device than are the Vulcan arrays, based on both measured results from the previous year (the Novan arrays had higher efficiency in a side-by-side test) and factory single-panel tests performed under controlled conditions. Both Vulcan and Novan performance test results for single panels are plotted on the operating curves to indicate where these solar panels are expected to operate. They appear to be operating near the Vulcan performance expectations.

Energy rejection occurred in all of the seven months. (December energy rejection was not available so the totals are for six months.) Over the six months, the collector array rejected a total of 18.1 million BTU, or an average of 3.02 million BTU/month. A typical month of rejected energy is shown in Figure 6. At 8:00 a.m. the most energy was rejected.

Figure 5a. Average Collector Efficiency
Wood Road School
October 1982

Figure 5b. Average Collector Efficiency
Wood Road School
December 1982

Figure 5c. Average Collector Efficiency
Wood Road School
January 1983

Figure 5d. Average Collector Efficiency
Wood Road School
February 1983

Figure 5e. Average Collector Efficiency
Wood Road School
March 1983

Figure 5f. Average Collector Efficiency
Wood Road School
April 1983

A profile of hourly average energy rejection for February 1983 is shown in Figure 6.

Figure 6. Collector Energy Rejection
Wood Road School
February 1983

The solar collector mounting location at large projects such as this one is critical, since long runs of exposed pipe will be expected to lose considerable amounts of heat, as well as to add costs to the system. Ideally, the collectors should be mounted as closely as possible to the storage tank and the loads.

Instrumentation problems caused by freezing of a flow meter in late December created a leak in the collector pipe system. This leak caused draindown of the system during the winter recess at the school.

Additional collector array problems were identified during a site visit to the school. Since the subarrays are mounted in a fairly close row configuration, there is some shading of the lower subarrays in the last three rows. Analysis of the data shows that operational incident radiation was lower in January (when the shading was most likely to occur).

Table 3 is a compilation of the collector operating characteristics over the seven-month period.

The overall collector transmittance absorptivity coefficient was 54%, which compares with the test results shown, although lower. Most large arrays have performance which is lower than single-panel test results. The heat loss coefficient was apparently lower than the factory test data shows, but, since this value is calculated over a narrow range of $(T_i - T_a)$, it is not a representative value.

Table 3. SOLAR COLLECTOR OPERATING CHARACTERISTICS

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

MONTH	COLLECTOR INTERCEPT (F_{Rta}) (%)	COLLECTOR HEAT LOSS (F_{RUL}) (BTU/FT ² -HR-°F)	CORRELATION COEFFICIENT	NUMBER OF POINTS (#)
OCT	55	-0.45	0.93	13
NOV	N.A.	N.A.	N.A.	0
DEC	N.A.	N.A.	N.A.	2
JAN	49	-0.50	0.48	20
FEB	53	-0.56	0.81	13
MAR	54	-0.51	0.97	17
APR	46	-0.62	0.95	32
AVERAGE	54	-0.54	-	-

TEST RESULTS - MANUFACTURER

MANUFACTURER	COLLECTOR INTERCEPT (F_{Rta}) (%)	COLLECTOR HEAT LOSS (F_{RUL}) (BTU/FT ² -HR-°F)
VULCAN (1)	73	-0.83
NOVAN (2)	62	-0.79

N.A. Denotes not applicable.

(1) Florida Solar Energy Center test data, corrected for gross area.

(2) Novan Energy, Inc., Boulder, Colorado, corrected for gross area.

2.2 STORAGE SUBSYSTEM

Energy flows into and out of the two 15,000-gallon storage tanks at the Wood Road School are presented in Table 4.

An estimated total of 686 million BTU was transferred to the storage tanks from the solar collector array.

Energy removed from storage included transfer to both space heating and Domestic Hot Water (DHW) subsystems, and totaled an estimated 480 million BTU.

Storage energy change was 7.32 million BTU.

Overall storage losses totaled an estimated 199 million BTU, or 28.3 million BTU/month. These losses were greater than during the previous season, and, in fact, were 29% of the collected energy.

Tank temperatures ranged from 149°F in October to 99°F in March. There were several times when tank temperatures were too low for utilization in the space heating subsystem.

The overall heat loss coefficient for the tanks averaged 0.23 BTU/ft²-hr-°F. The value was quite variable, ranging from 0.58 BTU/ft²-hr-°F to 0.10 BTU/ft²-hr-°F. No conclusions may be drawn from this, since some estimated energy flows are included in this analysis.

Table 4. STORAGE PERFORMANCE

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU, unless otherwise indicated)

MONTH	ENERGY TO STORAGE (STEI)	ENERGY FROM STORAGE (STEO)	CHANGE IN STORED ENERGY (STECH)	STORAGE EFFICIENCY (%) (STEFF)	AVERAGE STORAGE TEMPERATURE (°F) (TST)	EFFECTIVE HEAT LOSS COEFFICIENT (BTU/FT ² -HR-°F)	LOSS FROM STORAGE (STLOSS)
OCT	127	22.7	19.1	33	149	0.58	85.2
NOV	104 E	57.4	-17.0	40 E	129	0.51	63.6 E
DEC	60.0 E	45.1	-0.25	75 E	100	0.14	15.2 E
JAN	76.9	70.0 E	-4.07	69 E	117	0.10	11.0 E
FEB	118	110	5.25	98	118	*	2.75
MAR	76.9	66.1	3.86	31	99	*	6.94
APR	123	109	0.43	89	120	0.12	13.6
TOTAL	686 E	480 E	7.32	-	-	-	199 E
AVERAGE	98.0 E	68.6 E	1.05	69 E	119	0.23	28.3 E

E Denotes estimated value.

* Denotes unavailable data.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1

There are several possible reasons for the apparently poor storage tank performance at the school. These include:

- Poor location - the selected location of the tanks is in the collection field to the east of the array to facilitate drainage of the collector pipes. This location requires very long pipe lengths to return the warmed fluid to the building. A better location for such tanks in a cold climate is within the building structure, so that losses are both minimized and applied to the building heat load. Since the site required a drainback array, the effort and cost of burying the pipes below ground probably should have been expended in building a concrete-lined pit directly adjacent to the south wall of the school. If the pit were only covered with steel grate, it would still provide shelter for these tanks. The array probably could have been drained just as easily with this configuration. Some pipe and insulation would have been saved.

- Exterior tanks are subject to soaking and degradation of insulation, in addition to the fact that double tanks require more insulation per cubic foot of stored fluid.
- Original design drawings showed the collectors mounted on the roof of the school. This configuration probably would have increased performance, since:
 - Pipe runs would then be shorter, reducing losses.
 - Collector rows would be less shaded and less vulnerable to vandalism, etc.
 - The tanks would have been sheltered or interior-mounted.
 - More space would be available on school grounds.
 - Less framing material probably would have been required for a roof mount vs. field mount.
- Double tank configurations increase surface area - surface-to-volume ratios for this double-tank system are considerably larger than for an equivalent single-tank system. As an example, consider the following:
 - Two tanks at nine-foot diameter x 31-foot length
 - Surface area approximately 1,004 ft² per tank, total 2,008 ft².
 - Volume approximately 1,972 ft³ per tank, total 3,944 ft³
 - Surface to volume ratio = $2,008 / 3,944$
= 0.51 ft²/ft³
 - One tank at 12-foot diameter x 35-foot length
 - Surface area approximately 1,545 ft²
 - Volume approximately 3,958 ft³
 - Surface-to-volume ratio = $1,545 / 3,958$
= 0.39 ft²/ft³

Assuming an equivalent heat loss coefficient, insulation type and mounting configuration, the heat loss from the one-tank system should be about 24% less than from the two-tank system.

2.3 SPACE HEATING SUBSYSTEM

The space heating subsystem performance at the Wood Road School is presented in this section.

Tables 5 and 5a show the performance of the space heating subsystem during the seven-month time period.

Overall, performance was below design expectations.

Table 5. SPACE HEATING SUBSYSTEM

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU, unless otherwise indicated)

MONTH	SPACE HEATING LOAD (EHL)	CONTROLLED DELIVERED ENERGY (CDE)	TOTAL SOLAR ENERGY USED (HSE)	TOTAL AUXILIARY THERMAL USED (HAT)	SOLAR FRACTION OF LOAD (%) (HSFR)	AMBIENT TEMPERATURE (°F) (TA)
OCT	148	148	18.5 E	129	13 E	52
NOV	253	253	39.4 E	214	16 E	42
DEC	323	323	21.4 E	302	7	29
JAN	404	404	51.8 E	352	13	22
FEB	288	288	70.4 E	218	24	29
MAR	399	399	50.1 E	349	13	36
APR	326	326	80.4 E	246	24	44
TOTAL	2,140	2,140	332 E	1,810	-	-
AVERAGE	306	306	47 E	259	15 E	36

E Denotes estimated value.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1

The space heating load of 2,140 million BTU was provided through the use of 1,810 million BTU of auxiliary power (which includes the air handler's operating energy) and an estimated 332 million BTU of solar energy. The resulting solar fraction was an estimated 15% of the load.

Solar energy does not appear to be displacing auxiliary as much as it should, since auxiliary consumption was still high during periods of solar energy utilization.

Operating energy for the space heating subsystem pump totaled 59.8 million BTU, or 17,500 kwh.

Total heating degree-days were 6,051.

Table 5a. SPACE HEATING SUBSYSTEM (Continued)

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU, unless otherwise indicated)

MONTH	SPACE HEATING LOAD (EHL)	MEASURED SOLAR ENERGY USED (HSEM)	TOTAL OPERATING ENERGY (HOPE)	SOLAR- SPECIFIC OPERATING ENERGY (HOPEI)	AUXILIARY ELECTRICAL FUEL (HAE)	HEATING DEGREE- DAYS (#) (HDD)
OCT	148 E	18.5 E	4.49	4.49	129	430
NOV	253 E	39.4 E	11.8	11.8	214	689
DEC	323 E	21.4 E	5.74	5.74	302	1,048
JAN	404 E	51.8 E	9.68	9.68	352	1,348
FEB	288 E	70.4 E	10.0	10.0	218	1,040
MAR	399 E	50.1 E	6.06	6.06	349	891
APR	326 E	80.4 E	12.0	12.0	246	605
TOTAL	2,140 E	332 E	59.8	59.8	1,810	6,051
AVERAGE	309 E	47.0 E	8.54	8.54	259	864

E Denotes estimated value.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

Table 6 is a compilation of design data from the initial designs provided with the use of a design simulation program. A collector area of 20,000 square feet was assumed for the run.

These results are based on a predicted load totaling 1,840 million BTU, and a predicted contribution of 1,167 million BTU. The predicted solar fraction was 63% based on these numbers.

Actual performance was considerably lower than these predicted figures

Design weather conditions were sunnier and warmer than NSDN long-term data (see Section 3.3), but design heating degree-days seem to be very low.

Table 7 is a compilation of data on the electric power consumption for each of the sections of the school complex. "Total Complex Power" refers to the power consumption of both the Wood Road School section and the Milton Terrace School section, totaling 216,000 square feet. This value includes all electrical input for heat, lights, and equipment. "Wood Road School Total Power" is the total electrical energy consumed (not including solar energy) in the 136,510-square-foot Wood Road School section, which includes auxiliary heating energy, operating energy, DHW auxiliary power, and power for lights and equipment. "Wood Road School Strip Heat and Fans" refers to only the HVAC power consumption, and is equivalent to Heating Auxiliary Thermal Energy (HAT). "Milton Terrace School" is the total power consumed in the 79,490-square-foot Milton Terrace School section of the complex.

Table 6. DESIGN ASSUMPTIONS FOR THE WOOD ROAD SCHOOL
(Source: InterTechnology/Solar Corp.)
WITH 20,000 FT² SOLAR COLLECTORS

OCTOBER THROUGH APRIL

(All values in million BTU, unless otherwise indicated)

MONTH	DESIGN HEATING LOAD	DESIGN DHW LOAD	PREDICTED SOLAR CONTRIBUTION	HORIZONTAL SOLAR (BTU/FT ² -DAY)	DEGREE DAYS (#)	PREDICTED SOLAR FRACTION (%)
OCT	89	8.6	80	897	228	82
NOV	261	7.1	197	536	550	73
DEC	371	5.7	186	448	933	49
JAN	307	6.5	162	506	1,042	52
FEB	397	5.5	198	738	940	49
MAR	272	6.7	210	1,067	778	75
APR	141	7.7	134	1,355	465	90
TOTAL	1,840	47.8	1,167	5,547	4,936	-
AVERAGE	263	6.83	167	792	705	63

Table 7. TOTAL POWER CONSUMPTION AT THE
WOOD ROAD SCHOOL COMPLEX

OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU)

MONTH	TOTAL COMPLEX POWER	WOOD ROAD SCHOOL TOTAL POWER	WOOD ROAD SCHOOL STRIP HEAT AND FANS	MILTON TERRACE SCHOOL
OCT	306	153	129	153
NOV	598	313	214	284
DEC	779	440	302	339
JAN	832	487	352	344
FEB	642	439	218	204
MAR	692	437	349	255
APR	485	323	246	162
TOTAL	4,330	2,590	1,810	1,740
AVERAGE	619	370	259	249

The total complex power consumption averaged 619 million BTU/month, a seven-month total of 4,330 million BTU. This is equivalent to 1,270,000 kwh over the season.

The Wood Road School total power was 2,590 million BTU, or 370 million BTU per month. The electric power used at the Wood Road School for strip heaters and fans (not including DHW) was 1,810 million BTU.

The Milton Terrace School utilized 1,740 million BTU over the seven-month season.

Table 8 shows the power consumed at the complex in terms of BTU/ft²-Heating Degree-Day (HDD).

Over the seven-month period, the overall net complex power consumption was 3.31 BTU/ft²-HDD.

The Wood Road School net power consumption was 3.14 BTU/ft²-HDD, of which 2.59 BTU/ft²-HDD were attributable to heating. Solar contributed 0.40 BTU/ft²-HDD, and auxiliary contributed 2.19 BTU/ft²-HDD.

The Milton Terrace School used 3.62 BTU/ft²-HDD, or about 15% more power per square foot per heating degree-day than did the Wood Road School section.

Table 8. NET BUILDING LOADS

WOOD ROAD SCHOOL COMPLEX
OCTOBER 1982 THROUGH APRIL 1983

(All values in BTU/ft²-HDD, unless otherwise indicated)

MONTH	TOTAL COMPLEX POWER USE	WOOD ROAD SCHOOL TOTAL POWER	WOOD ROAD SCHOOL HEATING TOTAL	WOOD ROAD SCHOOL HEATING AUXILIARY	WOOD ROAD SCHOOL SOLAR ONLY	MILTON TERRACE TOTAL POWER	HEATING DEGREE- DAYS (#)
OCT	3.29	2.61	2.52	2.19	0.32	4.47	430
NOV	4.02	3.33	2.68	2.27	0.42	5.19	689
DEC	3.44	3.08	2.26	2.11	0.15	4.07	1,048
JAN	2.86	2.65	2.19	1.91	0.28	3.21	1,348
FEB	2.86	3.09	2.03	1.53	0.50	2.47	1,040
MAR	3.60	3.60	3.28	2.86	0.41	3.60	891
APR	3.71	3.91	3.95	2.98	0.97	3.37	605
TOTAL	-	-	-	-	-	-	6,051
WEIGHTED AVERAGE	3.31	3.14	2.59	2.19	0.40	3.62	864

The figures show that:

- The Wood Road School section was using less power per square foot per degree day than the Milton Terrace School section.
- Solar contribution at the Wood Road School was relatively minor at 0.40 BTU/ft²-HDD.
- Performance of the Wood Road School section has improved over the levels shown for the years 1972-1975, when the power consumption rates were above 12 BTU/ft²-HDD.

Bar charts depicting solar heating subsystem performance for each month of the reporting period are presented in Figures 7a through 7g.

These plots graphically demonstrate a large amount of information on the performance of the solar heating subsystem at the Wood Road School.

The top bar chart of each figure shows daily totals for Heating Degree-Days (HDD), measured using a 65°F reference temperature over each day. The height of the bar depicts the number of heating degree-days accumulated over 24 hours.

The center bars show both available solar radiation (the clear bar labeled "available") and collected solar radiation on a per square foot of solar collector area basis. Longer clear bars showing no darkened portion are an indication that available solar radiation was not collected.

The lower bars show the total building heat load, broken into auxiliary (darkened) and solar portion of the load. Days having small loads are easily seen, as are the effects of solar contribution.

Examining these plots can reveal quite a lot about the operation of the solar system over the entire season.

First, there are instances where solar energy was available and, for a variety of reasons, was not collected. The collectors may have been shut down on those days for testing, repair, etc. Also, on days having variable insolation levels, the time delay circuit on a large array such as the one at the Wood Road School will tend to keep the pump off (or on), thus losing some potentially collectible energy.

As previously described, the limiting factor as far as the collection subsystem was concerned was the high threshold losses.

Second, the application of solar energy often did not appear to reduce the total auxiliary electric power consumption, as mentioned later in the discussion of Figure 7f. The pattern of auxiliary use indicates that increased solar energy use does not decrease auxiliary use by a similar amount.

Figure 7a shows the performance of the system during October 1982. During October, there was a problem with the Site Data Acquisition Subsystem (SDAS) microcomputer which prevented data collection during 16 days of the month. Small heating loads at the beginning of the month were satisfied with auxiliary energy, yet solar energy was not collected or used for the first three days. Later in the month, the heating load increased above five million BTU/day.

The November performance is shown in Figure 7b. In general, the heating load was increasing in November. The weekends at the school show energy use which is reduced from the five-day work week. A sensor failure prevented measurement of collected solar energy after November 14. Small letter "Cs" in the collection blocks indicate the days during which the solar collectors operated.

December performance, shown in Figure 7c, was characterized by increasing loads and decreasing availability of solar energy. Very little solar energy was used after December 15. Note the drop in electric power consumption after December 23, representing the holiday period at the school. During this month, the flow rate was lowered in the space heating loop.

January data (Figure 7d) shows a still increasing heating load. There is indication that solar energy was not displacing auxiliary energy. Energy collection efficiency appears comparatively lower than expected. Peak heating loads appear to be near January 18 and 21.

February had significant data loss, as seen in Figure 7e. The heating load appears to be moderated during this month.

March performance is shown in Figure 7f.

First the solar collectors did not operate when they should have, perhaps due to system maintenance/repair or testing. There were 16 days during March which had insolation levels over 750 BTU/ft²-day (750 BTU/ft²-day is the approximate threshold level of insolation for this system). Of these days, there were seven days during which the collectors should have turned on and did not.

Secondly, solar energy does not appear to be displacing auxiliary electric energy.

The lower bar, auxiliary energy used, shows the weekend shutdown period quite clearly. Consider March 26, a weekend day, with an auxiliary consumption of 8.15 million BTU, heating degree-day value of 35, and 7.18 million BTU of solar energy used.

Compare March 26 with March 12, which was also a weekend day with lower auxiliary consumption. The auxiliary used on March 12 was 6.67 million BTU, with 31 heating degree-days. (Insolation was low on both days, so passive gains were not a factor.) Both days had nearly identical weather conditions, identical operating patterns (a weekend), yet solar energy was not used on March 12, because the storage tank was below 95°F. On March 26, a day when solar energy

Figure 7a. Space Heating Subsystem Performance
Wood Road School
October 1982

Figure 7b. Space Heating Subsystem Performance
Wood Road School
November 1982

Figure 7c. Space Heating Subsystem Performance
Wood Road School
December 1982

Figure 7d. Space Heating Subsystem Performance
Wood Road School
January 1983

Figure 7e. Space Heating Subsystem Performance
Wood Road School
February 1983

Figure 7f. Space Heating Subsystem Performance
Wood Road School
March 1983

was available from storage, there seems to be very little reduction in auxiliary use or substitution of solar energy for electric auxiliary. The solar energy appears to have been transferred and used along with about the same auxiliary energy as would have been consumed were there no solar available at all.

Control operation at projects with retrofit solar energy systems often allows the transfer of solar energy to the load while still consuming auxiliary energy at high rates. This operation causes the building to overheat.

During the weekdays, particularly the days after March 23, the same effect can be seen, although not as dramatically as on the weekend of March 26.

It should be noted that some percentage of the measured auxiliary use is attributed to fan power consumption, so a base load would be expected at the school even if no electric resistance heat were used.

Figure 7g is a presentation of April performance data. Heating degree-days were lower in April, and so was the heating load at the school. The lower bar chart shows 29 days utilizing solar energy, however the auxiliary use pattern still shows that solar energy use resulted in little displacement of auxiliary use. The control problem described for the March period appears to be continuing during April, although not as dramatically visible on the plot.

In general, energy savings were high this month, even though insolation was below expected and the ambient temperature was lower than expected. As compared to March, the system operation appeared to be improved. Examination of the center bar chart for April shows good collection on days when insolation was above 1,400 BTU/ft²-day.

Figure 7g. Space Heating Subsystem Performance
Wood Road School
April 1983

2.4 DOMESTIC HOT WATER SUBSYSTEM

Performance of the Domestic Hot Water (DHW) subsystem at the Wood Road School is presented in Table 9.

All values for total and DHW solar energy used in this report, except for October and November, are based on an estimated flow rate through the DHW heat exchanger. School personnel disconnected the meter which measures the flow rate, since the meter was causing noise and disturbing the students and teachers. The flow rate through the heat exchanger was measured during October and November, and this measured flow rate was then used in later months to estimate the solar contribution.

The total hot water load was an estimated 220 million BTU, of which an estimated 19% or 41.2 million BTU was supplied by the solar system.

A total of 178 million BTU was used by the three auxiliary tanks.

Table 9. DOMESTIC HOT WATER SUBSYSTEM

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU, unless otherwise indicated)

MONTH	HOT WATER LOAD (HWWL)	FRACTION OF LOAD (%) (HWSFR)	SOLAR ENERGY USED (HWSER)	AUXILIARY THERMAL USED (HWTAT)	AUXILIARY ELECTRICAL FUEL (HWAEL)	OPERATING ENERGY (HWOPE)
OCT	34.4	17	5.49	28.9	28.9	0.51
NOV	29.9	12	3.98	25.9	25.9	0.74
DEC	38.2 E	16 E	6.36 E	31.8	31.8	1.09
JAN	46.8 E	12 E	5.31 E	41.5	41.5	0.14
FEB	27.7 E	37 E	9.90 E	17.8	17.8	0.52
MAR	23.6 E	18 E	4.16 E	19.4	19.4	0.02
APR	19.0 E	31 E	5.95 E	13.0	13.0	0.00
TOTAL	220 E	-	41.2 E	178	178	3.02
AVERAGE	31.4 E	19 E	5.88 E	25.5	25.5	0.43

E Denotes estimated value.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

SECTION 3

OPERATING ENERGY, ENERGY SAVINGS, AND WEATHER CONDITIONS

3.1 OPERATING ENERGY

The operating energy requirements for the Wood Road School for the seven-month period are presented in Table 10.

Table 10. SOLAR OPERATING ENERGY

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU)

MONTH	ECSS OPERATING ENERGY			DHW OPERATING ENERGY (HWOPEI)	SHS OPERATING ENERGY (HOPEI)	TOTAL SOLAR OPERATING ENERGY (SYSOPEI)
	TOTAL ECSS (CSOPE)	COLLECTOR PUMP POWER (CSOPEI)	HEAT TRACE POWER (CSAUX)			
OCT	1.40	1.40	0.00	0.51	4.49	6.40
NOV	1.33	1.24	0.09	0.74	11.8	13.9
DEC	3.83	0.85	2.98	1.09	5.74	10.7
JAN	4.38	1.36	3.02	0.14	9.68	14.2
FEB	3.24	1.38	1.86	0.52	10.0	13.8
MAR	2.62	0.76	1.86	0.02	6.06	8.70
APR	2.43	1.63	0.80	0.00	12.0	14.4
TOTAL	19.2	8.62	10.6	3.02	59.8	82.1
AVERAGE	2.75	1.23	1.52	0.43	8.54	11.7

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

The electrical energy required to operate the system totaled 82.1 million BTU, or 11.7 million BTU/month. This is equivalent to 24,040 kwh. This monthly average of 11.7 million BTU/month is identical to the monthly solar operating energy measured the previous year.

The collection operating energy totaled 19.2 million BTU, which, as previously discussed, was comprised of 8.62 million BTU for pump operation and 10.6 million BTU for the operation of the electric heat trace on the collection loop.

The space heating subsystem pump used a total of 59.8 million BTU, or 17,510 kwh, over the season.

The DHW distribution pump required 3.02 million BTU of operating energy, equivalent to 884 kwh. This pump operated more during this season, as compared to the previous year when the value for the six-month season was 0.84 million BTU.

Note that power consumption of the air-handling units is not included in the system operating energy.

Related to operating energy is the solar system Coefficient of Performance (COP), shown in Table 11.

The COP provides a numerical value for the relationship of solar energy used or collected compared to the amount of electrical energy required to collect or deliver it. The greater the COP value, the more efficient the process. During the reporting period, the overall solar energy system provided an estimated weighted average solar COP value of 4.6. This was lower than the COP of 5.5 reported during the same period in 1981-1982. The decrease in COP was due to poorer solar energy utilization and more operating energy use (less effective use of pumps). The collection subsystem had an estimated COP of 80 compared to a COP of 53 the previous year. This value of 80 is based on the power consumption by the pump, not including the heat trace. If the collector heat trace is included in the COP, it drops to an estimated value of 36. The space heating subsystem solar COP was an estimated 5.6, lower than the 6.1 measured the previous year.

Heating COP decreased in November and December; this corresponds to the test period during which the solar hot water loop flow was reduced (see Appendix A-2).

Hot water COP averaged an estimated 14; however, the monthly values exhibit a large variation. The COP values for hot water are not entirely accurate, since the hot water circulation pump does not supply energy to the hot water subsystem when the space heating distribution pump is operating. A COP for the combined heating and hot water subsystems was 6.0, which is similar to the heating subsystem COP. The combined COP shows a fairly steady improvement through the season.

Table 11. SOLAR COEFFICIENT OF PERFORMANCE

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

MONTH	SOLAR ENERGY SYSTEM ($\frac{SEL}{SYCOPCT}$)	COLLECTION SUBSYSTEM (PUMP ONLY) ($\frac{SECA}{CSOPCT}$)	COLLECTION SUBSYSTEM OVERALL ($\frac{SECA}{CSOPCT}$)	DOMESTIC HOT WATER SOLAR ($\frac{HWSL}{HWOPCT}$)	SPACE HEATING SOLAR ($\frac{HSEM}{HWOPCT}$)	COMBINED DHW/SH LOOP ($\frac{SEL}{(HWOPEI + HOPEI)}$)
OCT	3.8 E	91	91	11 E	4.1 E	4.8 E
NOV	3.1 E	84	78	5.4 E	3.3 E	3.5 E
DEC	2.6 E	71 E	16 E	5.8 E	3.7 E	4.1 E
JAN	4.0 E	57	18	38 E	5.4 E	5.8 E
FEB	5.8 E	86	36	19 E	7.0 E	7.6 E
MAR	6.2 E	101	29	210 E	8.3 E	8.9 E
APR	6.0 E	75	51	-	6.7 E	7.2 E
WEIGHTED AVERAGE	4.6 E	80 E	36 E	14 E	5.6 E	6.0 E

E Denotes estimated value.

For a description of acrynyms in parentheses, refer to Appendix C of Reference 1.

3.2 ENERGY SAVINGS

Energy savings at the Wood Road School are based on the following assumptions:

- Heating units consume electric power to supply heat to the building. Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet demands which would otherwise be met by electrical power. The operating energy required to transport solar energy from the collector to storage and to the loads is subtracted from the solar energy contribution to the loads to determine net savings by subsystem.
- Collector heat trace power is considered an operating expense.
- Wood Road School has a total area of 136,510 square feet which is solar conditioned.
- Savings due to conservation measures are not included in these calculations. Also, the impact of overheating (if any) was not addressed in calculation of energy savings.

Energy savings for the Wood Road School from October 1982 through April 1983 are presented in Table 12. During the seven-month period, the total savings were an estimated 291 million BTU of electrical energy. These savings are equivalent to 85,200 kwh.

Compared to the previous year, savings were lower, as described in Section 1.1.

Table 12. ENERGY SAVINGS

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in million BTU)

MONTH	SOLAR ENERGY USED (SEL)	SPACE HEATING ELECTRICAL (HSVE)	DOMESTIC HOT WATER ELECTRICAL (HWSVE)	ECSS OPERATING ENERGY SOLAR-UNIQUE (CSOPE)	NET ENERGY SAVINGS ELECTRICAL (TSVE)
OCT	24.0 E	14.0 E	4.98	1.40	17.6 E
NOV	43.4 E	27.6 E	3.24	1.33	29.5 E
DEC	27.8 E	15.7 E	5.27	3.83	17.1 E
JAN	57.1 E	42.1 E	5.17 E	4.38	42.9 E
FEB	80.3 E	60.4 E	9.38 E	3.24	66.5 E
MAR	54.3 E	44.0 E	4.18 E	2.62	45.5 E
APR	86.3 E	68.4 E	5.95 E	2.43	71.9 E
TOTAL	373 E	272 E	38.1 E	19.2	291 E
AVERAGE	53.3 E	38.9 E	5.45 E	2.75	41.6 E

E Denotes estimated value.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

Table 13 is a compilation of energy savings at the Wood Road School site, normalized to BTU/ft²-day per unit collector area.

Note that the net savings per square foot of solar collector averaged 62.3 BTU/ft²-day, as compared to the incident radiation of 1,032 BTU/ft²-day.

This table also illustrates the losses incurred from collection through utilization of the solar energy.

Table 13. NET ENERGY SAVINGS PER UNIT COLLECTOR AREA

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

(All values in BTU/ft²-day)

MONTH	NET SOLAR AVAILABLE (SEA)	NET SOLAR COLLECTED (SECA)	NET SOLAR UTILIZED (SEL)	NET SOLAR SAVINGS (TSVE)
OCT	1,515	186	35.1 E	25.8 E
NOV	828	157	65.6 E	44.6 E
DEC	648	87.8 E	40.7 E	25.0 E
JAN	945	113	83.6 E	62.8 E
FEB	1,129	191	130 E	108 F
MAR	1,082	113	79.5 E	66.6 E
APR	1,075	186	131 E	109 E
TOTAL	7,222	-	-	-
AVERAGE	1,032	147 E	79.8 E	62.3 E

E Denotes estimated value.

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

3.3 WEATHER CONDITIONS

Table 14 presents the actual weather conditions and the long-term average conditions for solar radiation in the plane of the collector array, ambient temperature, heating and cooling degree-days.

Insolation averaged 1,032 BTU/ft²-day, about five percent higher than expected. April data showed the most decrease in solar radiation compared to expected, while October data was larger than the expected value. Ambient temperature was 1°F warmer than expected. Heating degree-days were 6,051 vs. 6,430 expected.

Table 14. WEATHER CONDITIONS

WOOD ROAD SCHOOL
OCTOBER 1982 THROUGH APRIL 1983

MONTH	DAILY INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/FT ² -DAY)		AMBIENT TEMPERATURE (°F)		HEATING DEGREE-DAYS	
	MEASURED (SE)	LONG-TERM AVERAGE	MEASURED (TA)	LONG-TERM AVERAGE	MEASURED (HDD)	LONG-TERM AVERAGE
OCT	1,515	1,165	52	51	430	422
NOV	828	769	42	40	689	762
DEC	648	672	29	26	1,048	1,212
JAN	945	855	22	22	1,348	1,349
FEB	1,129	1,048	29	24	1,040	1,162
MAR	1,082	1,167	36	33	891	980
APR	1,075	1,243	44	47	605	543
TOTAL	7,222	6,919	-	-	6,051	6,430
AVERAGE	1,032	988	36	35	864	919

For a description of acronyms in parentheses, refer to Appendix C of Reference 1.

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SECTION 4

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3. 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
4. E. Streed, et al, Thermal Data Requirements and Performance Evaluation Procedures for the National Heating and Cooling Demonstration Program, NBSIR 76-1137, National Bureau of Standards, Washington, D.C., 1976.
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- *6A. User's Guide to Monthly Performance Reports, November 1981, SOLAR/0004-80/18, Vitro Laboratories, Silver Spring, Maryland.
- *6B. Instrumentation Installation Guidelines, March 1981, Parts 1, 2, and 3, SOLAR/0001-81/15, Vitro Laboratories, Silver Spring, Maryland.
7. Monthly Performance Report, Wood Road School, October 1982, Vitro Laboratories, Silver Spring, Maryland.
8. Monthly Performance Report, Wood Road School, November 1982, Vitro Laboratories, Silver Spring, Maryland.
9. Monthly Performance Report, Wood Road School, December 1982, Vitro Laboratories, Silver Spring, Maryland.
10. Monthly Performance Report, Wood Road School, January 1983, Vitro Laboratories, Silver Spring, Maryland.
11. Monthly Performance Report, Wood Road School, February 1983, Vitro Laboratories, Silver Spring, Maryland.

* Copies of these reports are available from the U.S. Department of Energy, Technical Information Center, P.O. Box 62, Oak Ridge, TN 37830.

12. Monthly Performance Report, Wood Road School, March 1983, Vitro Laboratories, Silver Spring, Maryland.
13. Monthly Performance Report, Wood Road School, April 1983, Vitro Laboratories, Silver Spring, Maryland.
- *14. Comparative Report: Performance of Active Solar Space Heating Systems, 1981-1982 Heating Season, SOLAR/0025-83/42, Vitro Laboratories, Silver Spring, Maryland.
15. Technical Proposal (for the Wood Road School Solar Project), Vol. II, submitted by Ballston Spa Central School District to ERDA/DOE for PON II Demonstration Cycle, 1976.

* Copies of this report are available from the U.S. Department of Energy, Technical Information Center, P.O. Box 62, Oak Ridge, TN 37830.

APPENDIX A

SYSTEM DESCRIPTION

A-1 SYSTEM DESCRIPTION

A-2 SITE HISTORY, PROBLEMS,
AND MODIFICATIONS

APPENDIX A-1
SYSTEM DESCRIPTION

The Wood Road School Solar Project of the Ballston Spa Central School District is a cooperative experimental solar system designed to provide hot water and heating contributions to the Wood Road Elementary School in Ballston Spa, New York.

The project was funded by the School District, the New York State Department of Education, the New York State Energy Research and Development Authority, and the U.S. Department of Energy under the Solar Heating and Cooling Demonstration Program PON-2 cycle. Monitoring of the performance of the system has been undertaken through a joint effort by Niagara-Mohawk Electric Power Company (and their subcontractor, Trautman Associates) and the Department of Energy.

The solar collector array consists of 861 solar collectors mounted in a series of south-facing wooden frames at a 22 degree west azimuth tilted to an angle of 60 degrees from the horizontal. The 22,039-square-foot array consists of 591 Vulcan Model CC-1F/G and 270 Novan Model 98SC solar collectors, which use treated water as the heat transfer medium in a draindown mode for freeze protection. Storage is provided by two 15,000-gallon horizontally mounted cylindrical tanks located adjacent to the collector array above ground. Three pumps and associated controls are housed in a shed adjacent to the storage tanks, which are coated with six inches of isocyanurate insulation.

The manufacturers of the major solar system equipment and components are listed below.

<u>Equipment/Components</u>	<u>Manufacturer</u>	<u>Model No.</u>
Solar Collectors	Vulcan	CC-1F/G
Solar Collectors	Novan	98SC
Collector Pump P1	Lincoln Electric	T2556 (15 hp)
Heating Distribution P2	Lincoln Electric	TV3012 (10 hp)
Hot Water Distribution P3	Bell & Gossett (ITT)	M98551 (1 hp)
Heat Exchanger	Bell & Gossett (ITT)	

The system, shown schematically in Figures A-1, A-2, and A-3, operates in three modes.

Mode 1 - Collector-to-Storage and Drainback - Pump P1 activates when a control temperature sensor located on the collector array is 25°F higher than a control sensor located in the storage vessel. The collector pump deactivates when the collector plate temperature is less than 3°F greater than the storage tank temperature. Valve V-8 opens when pump P1 deactivates, which facilitates drainback of the collector fluid. In addition, a second control circuit prevents collector operation if the storage temperature exceeds 185°F. A time delay circuit is included to prevent short cycling of pump P1.

Mode 2 - Storage-to-Space Heating - Hot water supply pump P2 activates when the outdoor ambient temperature falls below 60°F and the storage tank is above 95°F. Once energized, the pump will operate until the ambient temperature exceeds 60°F or the storage tank temperature falls to 85°F. When pump P2 de-energizes, valve V-2 automatically closes. Room thermostats modulate the hot water in the various zones of the school.

Mode 3 - Storage-to-Domestic Hot Water - Pump P3 is controlled by a temperature comparator which receives signals from control sensors located in the Domestic Hot Water (DHW) heat exchanger head and the storage tank. If pump P2 is not already activated, pump P3 will switch on whenever the storage tank temperature is 20°F greater than the heat exchanger. A time delay relay keeps the pump "energized" or "de-energized" for at least 15 minutes. Valve V-3 maintains a constant output temperature from the DHW heat exchanger.

APRIL 2, 1982

Figure A-1. Wood Road School Solar Energy System Schematic

- *W101, W151 PANELS FLOW (RATE)*
- ▼ *T101, T151 LOWER PANELS INLET TEMP*
- ▼ *T102, T152 LOWER PANELS OUTLET/UPPER PANELS INLET TEMP*
- ▼ *T103, T153 UPPER PANELS OUTLET TEMP*

APRIL 2, 1982

Figure A-2. Wood Road School Solar Collector Array and Instrumentation

APRIL 2, 1982

Figure A-3. Wood Road School Electrical and Domestic Hot Water Sensor Locations

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APPENDIX A-2

SITE HISTORY, PROBLEMS, AND MODIFICATIONS

(This section covers June 1982 through April 1983)

Date

Event

6/14/82

Vitro analyst discussion with Wood Road School. Site down for summer months. Problems included:

- Corroded thermometer well

A steel thermometer well located in one of the storage tanks failed in February 1982. The thermowell houses the storage control sensor for activation of the collector array pump. Corrosion at an apparent water/air interface on the well caused a leakage of fluid from the tank, which affected the control of the array. The pump was on manual control until April 1982. The well was repaired in September of 1982. During February 1983, Vitro analyzed the thermowell, and recommended addition of fluid treatment to prevent further damage.

- Precipitate blockage

Several collector arrays, including the instrumented Novan array, suffered blockage due to a precipitate in the collector tubes. Evaporating collector fluid which remains after drainback may cause this effect. It is not known how many collectors are blocked and to what extent this blockage affects thermal performance.

- Pipe insulation

Excessive losses were identified during the spring of 1982 in the pipes leading from the storage tanks to the load. Some of this insulation was replaced over the summer of 1982. Losses did improve in 1983 as compared to 1982.

10/3/82

The solar system remained inoperative until the first part of October 1982.

<u>Date</u>	<u>Event</u>
11/10/82	Wood Road School personnel lowered flow rate by 25% in the main heat distribution loop in order to increase building temperature drop across terminals. Data showed no significant improvement in performance or resolution of drop.
11/15/82	Temperature probe T451 was reading 2-3°F too high. SDAS component later found to be cause of problem. Bias on sensor removed in software workaround. As a result, there are estimated values for HSE (solar energy to space heating subsystem). T150, collector array outlet temperature probe, was reading 6-10°F higher than expected. No workaround available.
11/23/82	Temperature probe T451 repaired.
12/6/82	Data now showed anomalous readings from three critical probes, T400, T401, and T451. Probes replaced and new calibration coefficients entered in software. Estimates of HSE used by looking at energy from storage and reducing energy to building by amount equal to loss rate in pipes measured in October 1982. This workaround continued throughout spring of 1983.
12/23/82	System load decreased due to vacation at school.
12/28/82	Freeze failure of flow meters W151 and W101. Strap holding meters worked loose. DHW flow meter WT300 removed due to noise created in classroom. Previous values for flow rate now used in software.
1/6/83	Temperature probe T150 replaced. Collection subsystem again working after repairs. Flow rate increased to normal in main loop.
2/4/83	SDAS main chassis replaced. New filtered power supply added to prevent interference from line voltage spikes.
4/14/83	Several temperature probes bath tested in controlled temperature bath. Results indicated temperature probe T400 was reading slightly lower than expected. Bias removed in software to provide a new data estimate for HSE.

APPENDIX B
DATA ACCURACY

APPENDIX B

DATA ACCURACY

INTRODUCTION

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

DATA ACCURACY ESTIMATES

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

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

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

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

Table B-1. SENSOR ACCURACY
THE NATIONAL SOLAR DATA NETWORK

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX B

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- B-1 Streed, E., et al. Thermal Requirements and Performance Evaluation Procedures for the National Heating and Cooling Demonstration Program, NBSIR 76-1137, National Bureau of Standards, Washington, D.C., 1976.
- B-2 Seropian, A. Data Accuracy Study (Two Parts), Technical Memo #03200.8, Vitro Laboratories, Silver Spring, Maryland, March 13, 1981.