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# ROBERTS HOME

# RESTON, VIRGINIA

# SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

# FEBRUARY 1982 THROUGH JULY 1982

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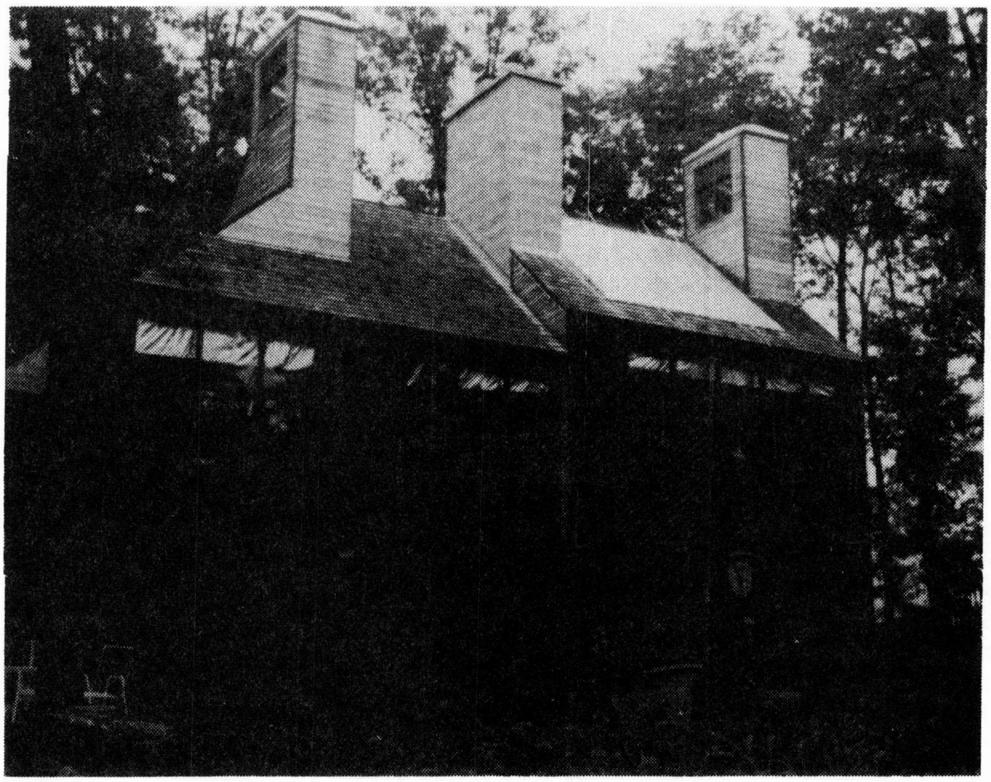
# FOREWORD

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.



ROBERTS HOME

# ROBERTS HOME

The Roberts Home is a 2,300-square-foot single family residence in Reston, Virginia. The passive solar heating and cooling system consists of the following elements:

| | |
|---|---|
| Collectors: | Trombe wall with 663 square feet of one-fourth-inch Plexiglass® glazing. Thermal Technology Corporation R-12 reflective automated movable insulation. |
| Storage: | Three sections: Trombe wall, rear air-core mass wall and a central core. Total mass 264,000 pounds. Concrete masonry construction. |
| Sunspace: | 99 square feet of Plexiglass® at 48 degree tilt. |
| Auxiliary: | Electric baseboard heaters, three window-mounted heat pumps, two fireplaces. |

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# SECTION 1

# SOLAR SYSTEM PERFORMANCE

## ROBERTS HOME
## FEBRUARY 1982 THROUGH JULY 1982

### Heating Season
### February 1982 through April 1982

| | |
|---|---|
| Building Solar Fraction[1] | 52 |
| Equipment Solar Fraction[2] | 82 |
| Conventional Fuel Savings[3] | 4,512 kwh |

### Seasonal Energy Requirements
### February 1982 through July 1982
### (Million BTU)

| | Equipment Heating/Cooling Load | Solar Contribution | % Solar |
|---|---|---|---|
| Heating | 19.5 | 15.9 | 82 |
| Cooling | 21.2 | 21.2 | 100 |

### Environmental Data

| | Measured Average | Long-Term Average |
|---|---|---|
| Outdoor Temperature | 58°F | 56°F |
| Heating Degree-Days (Total) | 1,818 | 2,091 |
| Cooling Degree-Days (Total) | 719 | 564 |
| Daily Incident Solar Energy | 507 BTU/ft² | 831 BTU/ft² |

1. Building Solar Fraction $= \dfrac{\text{Passive Solar Energy Consumed (HSEP)}}{\text{Building Load (BL)}} \times 100$

2. Equipment Solar Fraction $= \dfrac{\text{Passive Solar Energy Consumed (HSEP)}}{\text{Equipment Heating Load (EHL)}} \times 100$

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

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

## 1.1 SUMMARY AND CONCLUSIONS

The Roberts Home in Reston, Virginia is equipped with a passive space heating and cooling system. The passive solar heating system provided 82% of the equipment heating load of 19.5 million BTU for the three-month period, February 1982 through April 1982. A summary of the passive heating system performance is presented in Table 1 and Figure 1.

The net electrical energy savings from the passive solar space heating system were 4,512 kwh or $271 at an average electrical power cost of $0.06 per kwh.

Space heating for the Roberts Home is supplied by three sections of two-story Trombe wall and a sunspace located on the third floor. Solar energy is stored in the 12-inch Trombe wall, the hollow core north wall, and the masonry walls of two centrally located fireplaces. Four fans draw air from the space between the Trombe wall and the glazing through the north wall core. Three R-12 Thermal Technology curtains reduce nighttime losses from the Trombe wall. The house walls are insulated to R-24 and the roof to R-32. Double-glazed Pella windows are used throughout the house. Backup heat is supplied by electric baseboard heaters and three window-mounted heat pumps.

### Table 1. SPACE HEATING THERMAL PERFORMANCE

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | EMPIRICAL HEATING DEGREE-DAYS (#) (HDD) | BUILDING SOLAR FRACTION (%) (BHSFR) | BUILDING HEAT LOAD (BL) | CONDUCTION LOSSES (UAΔT) (HLUA) | INFIL LOSSES (HI) | INTERNAL GAINS (HOTHER) | AUX ENERGY CONSUMED (HAT) | PASSIVE SOLAR ENERGY CONSUMED (HSEP) | EQUIPMENT HEATING LOAD (EHL) | EQUIPMENT SOLAR FRACTION (%) (EHSFR) |
|---|---|---|---|---|---|---|---|---|---|---|
| FEB | 729 | 46 | 11.2 | 8.10 | 3.08 | 3.64 | 2.43 | 5.12 | 7.54 | 68 |
| MAR | 649 | 50 | 10.5 | 7.74 | 2.73 | 4.07 | 1.15 | 5.24 | 6.39 | 85 |
| APR | 395 | 64 | 8.68 | 6.63 | 2.05 | 3.14 | 0.00 | 5.54 | 5.54 | 100 |
| TOTAL | 1,773 | - | 30.4 | 22.5 | 7.86 | 10.9 | 3.58 | 15.9 | 19.5 | - |
| AVERAGE | 591 | 52 | 10.1 | 7.49 | 2.62 | 3.62 | 1.19 | 5.30 | 6.49 | 82 |

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

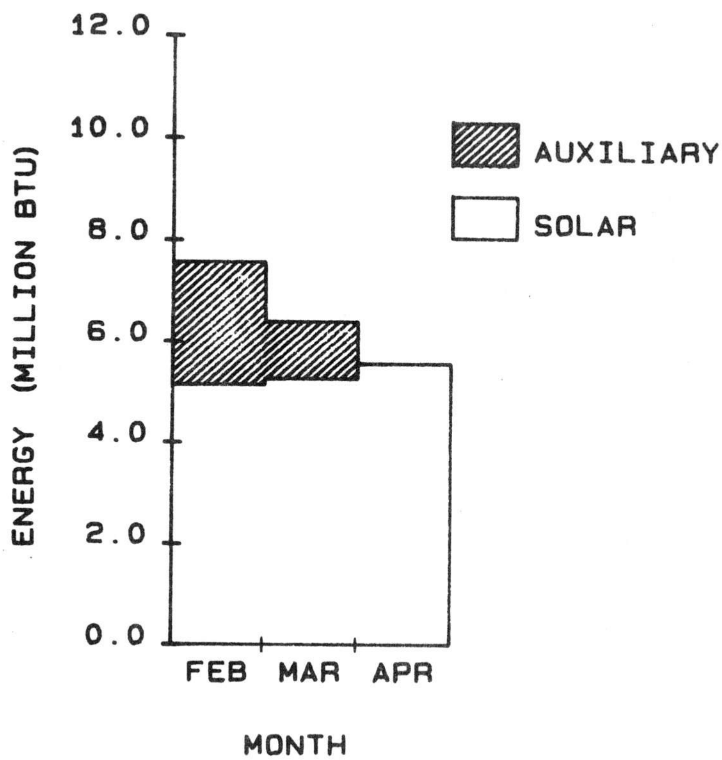



Figure 1. Space Heating Thermal Performance
Roberts Home
February 1982 through April 1982

The net electrical energy savings from the passive cooling system were $144 for the period May 1982 through July 1982.

In the cooling season, the thermal curtain is closed during the day to avoid solar gain, and opened at night. The sunspace glazing is protected by roll-down metal decking. Two thermal chimneys, which are glazed at the top with Plexiglass® to admit solar energy, assist in convecting warm air out of the building. A set of cooling tubes supplies cool air to the bottom of the Trombe wall cavity. The cool air is drawn past the wall's surface, between the thermal curtain and the wall, when the curtain is down. To assist in the transfer of heat from room air to the masonry mass, a small oscillating fan in each of the main living areas is used for about 12 hours per day. Three heat pumps provide auxiliary cooling.

The passive space cooling system performance is presented in Table 2.

## Table 2. SPACE COOLING THERMAL PERFORMANCE

### ROBERTS HOME
### MAY 1982 THROUGH JULY 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | EMPIRICAL COOLING DEGREE-DAYS (#) (CDD) | PASSIVE COOLING SOLAR FRACTION (%) (CSFR) | BUILDING COOLING LOAD (CL) | EQUIPMENT COOLING LOAD (ECL) | CONDUCTION LOSSES (UAΔT) (HLUA) | NET SOLAR GAIN (NET_GAIN) | RADIANT COOLING NET LOAD (NET_RAD_GAIN) | INTERNAL GAINS (HOTHER) | AUXILIARY THERMAL (CAT) | PASSIVE SOLAR COOLING (CSEP) | STORAGE TEMP (°F) (TST) | BUILDING TEMP (°F) (TB) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAY | 125 | 100 | 6.86 | 4.95 | 1.91 | 1.67 | 3.34 | 1.85 | 0.00 | 4.95 | 70 | 72 |
| JUN | 217 | 100 | 8.10 | 6.59 | 1.51 | 1.76 | 3.87 | 2.47 | 0.00 | 6.59 | 72 | 73 |
| JUL | 377 | 99 | 9.84 | 9.69 | 0.15 | 1.77 | 5.23 | 2.81 | 0.07 | 9.62 | 76 | 77 |
| TOTAL | 719 | - | 24.8 | 21.2 | 3.57 | 5.20 | 12.4 | 7.13 | 0.07 | 21.2 | - | - |
| AVERAGE | 240 | 100 | 8.27 | 7.08 | 1.19 | 1.73 | 4.15 | 2.38 | - | 7.05 | 73 | 74 |

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

Highlights of the performance of the Roberts Home during the six-month monitoring period are:

- The building heat load was met by 52% solar, 36% internal gains, and 12% auxiliary heat.
- The solar energy used was 65% from the Trombe wall and 35% from the sunspace.
- The Trombe wall had a 20% net gain of incident solar and the sunspace had a 19% net gain.
- The nonsolar energy used per heating degree-day per square foot of floor area was 3.48 BTU/heating degree-day/ft$^2$.
- Compared to a well-insulated home in the same area with a monitored load of 5.94 BTU/heating degree-day/ft$^2$, the Roberts Home had a 41% heating savings.
- Compared to a direct-gain, low-mass, well-insulated home in the same area with a monitored load of 4.74 BTU/heating degree-day/ft$^2$, the Roberts Home had a 26% heating savings.
- The passive cooling system provided over 99% of the building cooling load.
- The nonsolar energy used for cooling per cooling degree-day per square foot of floor area was 3.92 BTU/cooling degree-day/ft$^2$.

- The combination of high mass, movable insulation, cooling tubes, thermal chimneys, exterior shading on the sunspace glazing, and shading by the trees on the site prevented the building from overheating on warm sunny summer days.

- The net savings in heating and cooling energy for the period from February 1982 through July 1982 were $415.

The flow of solar energy and auxiliary energy is shown in the heating Energy Flow Diagram, Figure 2, and the cooling Energy Flow Diagram, Figure 3.

The cooling Energy Flow Diagram, Figure 3, is similar to the heating Energy Flow Diagram, but contains performance values for the summer months. The energy collection and storage subsystems do not contribute at all to cooling the house; in fact, they contributed 5.20 million BTU of unwanted heat. Solar cooling is reflected in the arrow labeled "PASSIVE SOLAR," and only in that arrow. The effects of ventilation are also included in the "PASSIVE SOLAR" arrow, because much of the ventilation was assisted by the thermal chimneys.

The 3.99 million BTU of vented energy from the energy collection subsystem were vented out the thermal chimneys without contributing to the cooling load of the house.

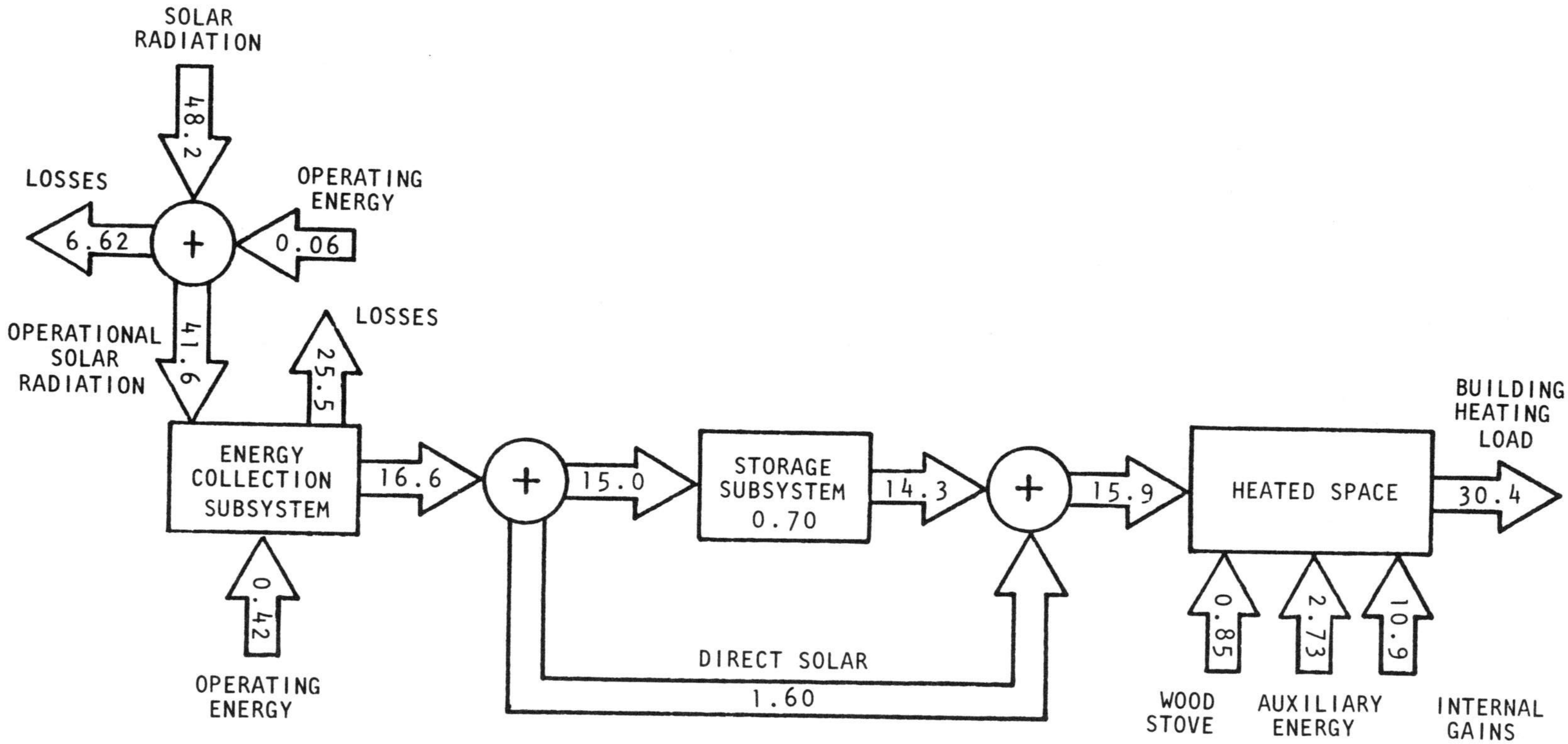



Figure 2. Heating Energy Flow Diagram for Roberts Home
February 1982 through April 1982
(Figures in million BTU)

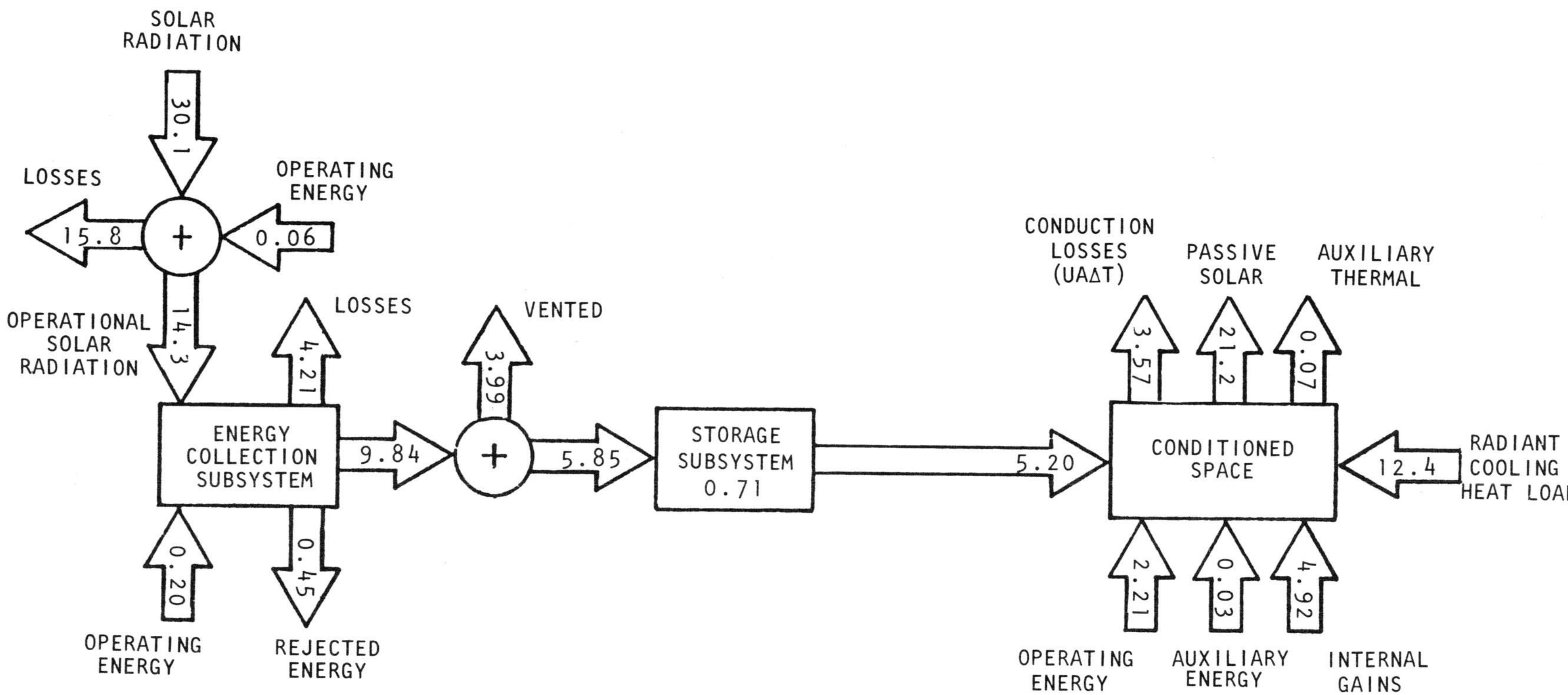



Figure 3. Cooling Energy Flow Diagram for Roberts Home
May 1982 through July 1982
(Figures in million BTU)

## SECTION 2

## SUBSYSTEM PERFORMANCE

### 2.1 ENERGY COLLECTION SUBSYSTEM

The Trombe wall and sunspace collection subsystem performance during three months of the heating season, February 1982 through April 1982, is presented in Table 3.

There were 48.2 million BTU of incident solar energy. A total of 41.7 million BTU or 87% of the available solar energy was incident on the glazing when the automated movable insulation system was open. Forty percent of the operational incident solar energy, or 16.6 million BTU, was transmitted and collected by the collectors. Of the 16.6 million BTU that were collected, 7.80 million BTU were lost back through the glazing, resulting in a net solar gain of 8.79 million BTU or 18% of the incident solar energy.

The movable insulation was in place for an average of 18 hours per day and used 0.48 million BTU to operate it.

Table 3. TROMBE WALL AND SUNSPACE COLLECTION SUBSYSTEM PERFORMANCE, HEATING SEASON

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | TOTAL INCIDENT SOLAR RADIATION (SEA) | TOTAL OPERATIONAL INCIDENT ENERGY (SEOP) | SOLAR ENERGY COLLECTED/ TRANSMITTED (SECA) | OPERATING COLLECTOR TRANSMITTANCE (%) (SEOP_TRANS) | TOTAL ECSS OPERATING ENERGY (SYSOPE) | COLLECTOR LOSS (SG_HL) | COLLECTOR NET GAIN (NET_GAIN) | MOVABLE INSULATION IN PLACE (HOURS/DAY) (MI_TIME) |
|---|---|---|---|---|---|---|---|---|
| FEB | 15.3 | 12.5 | 5.44 | 44 | 0.17 | 3.54 | 1.90 | 19 |
| MAR | 15.0 | 12.8 | 5.36 | 42 | 0.25 | 2.32 | 3.04 | 20 |
| APR | 17.9 | 16.4 | 5.79 | 35 | 0.06 | 1.94 | 3.85 | 16 |
| TOTAL | 48.2 | 41.7 | 16.6 | - | 0.48 | 7.80 | 8.79 | - |
| AVERAGE | 16.1 | 13.9 | 5.53 | 40 | 0.16 | 2.60 | 2.93 | 18 |

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

The performance of the Trombe wall collection subsystem during three months of the heating season, February 1982 through April 1982, is presented in Table 4.

Table 4. TROMBE WALL COLLECTION SUBSYSTEM PERFORMANCE, HEATING SEASON

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | INCIDENT SOLAR RADIATION (SEA_TW) | OPERATIONAL INCIDENT SOLAR ENERGY (SEOP_TW) | COLLECTED SOLAR ENERGY (SECA_TW) | NET GAINS (NET_GAIN_TW) | OVERALL COLLECTOR EFFICIENCY (%) (CLEF_TW) |
|---|---|---|---|---|---|
| FEB | 12.6 | 9.73 | 3.67 | 1.56 | 20 |
| MAR | 12.3 | 9.61 | 3.32 | 2.39 | 19 |
| APR | 13.7 | 12.2 | 3.73 | 2.92 | 21 |
| TOTAL | 38.6 | 31.5 | 10.72 | 6.87 | - |
| AVERAGE | 12.8 | 10.5 | 3.57 | 2.29 | 20 |

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

The incident insolation on the collector, when the movable insulation system was open, was 31.5 million BTU. This is 82% of the total 38.6 million BTU incident on the Trombe wall during the heating period. The Trombe wall collected 10.7 million BTU, but losses from the single glazing resulted in a net gain of only 6.87 million BTU. This represents 18% of the incident solar energy during the heating season.

The performance of the sunspace-greenhouse collection subsystem for three months of the heating season, February 1982 through April 1982, is presented in Table 5.

Table 5. SUNSPACE-GREENHOUSE COLLECTION SUBSYSTEM PERFORMANCE, HEATING SEASON

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | INCIDENT SOLAR RADIATION (SEA_SS) | TRANSMITTED SOLAR ENERGY (SECA_SS) | NET GAINS (NET_GAIN_SS) | OVERALL COLLECTOR EFFICIENCY (%) (CLEF_SS) | AVERAGE SUNSPACE TEMP (°F) (SS_TA) | AVERAGE SUNSPACE TEMP AT ± 3 HRS TSN (°F) (SS_TDA) | MAXIMUM SUNSPACE TEMP (°F) (SS_TA_MAX) | AIR-CORE FANS OPERATING ENERGY (CSOPE_FAN) |
|---|---|---|---|---|---|---|---|---|
| FEB | 2.72 | 1.77 | 0.34 | 13 | 61 | 68 | 92 | 0.15 |
| MAR | 3.14 | 2.04 | 0.65 | 21 | 64 | 70 | 105 | 0.23 |
| APR | 4.20 | 2.06 | 0.93 | 22 | 70 | 78 | 97 | 0.04 |
| TOTAL | 10.1 | 5.87 | 1.92 | - | - | - | - | 0.42 |
| AVERAGE/ MAXIMUM | 3.35 | 1.96 | 0.64 | 19 | 65 | 72 | 105 | 0.14 |

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

Of the 10.1 million BTU incident on the sunspace glazing during the heating season, 5.87 million BTU were transmitted, resulting in an average transmittance for the greenhouse glazing system of 58%. The net gain of the sunspace was 1.92 million BTU or 19% of the incident solar energy available. The daily average sunspace temperature was 65°F. The average midday temperature was 72°F and the maximum temperature was 105°F. The air-core fans which draw air from the Trombe wall and sunspace consumed 0.42 million BTU, or 123 kwh at a cost of about $7.38 for electricity purchased at $0.06 per kwh.

The Trombe wall and sunspace collection subsystem performance during three months of the cooling season, May 1982 through July 1982, is presented in Table 6.

For the three-month period, there were 30.1 million BTU of incident solar energy. A total of 14.3 million BTU or 48% of the available solar energy was incident on the glazing when the movable insulation was open. The transmitted solar energy was only 5.85 million BTU or 41% of the operational incident. This was due to the shading of the sunspace, the increased angle of incidence on the Trombe wall reducing the glazing transmittance, and venting of the space between the Trombe wall and the glazing. Of the 5.85 million BTU collected, 3.09 million BTU were lost back through the glazing, producing a net solar gain of 2.76 million BTU. The movable insulation was in place for an average of 10.1 hours per day and used 0.20 million BTU to operate it.

Table 6. TROMBE WALL AND SUNSPACE COLLECTION SUBSYSTEM PERFORMANCE, COOLING SEASON

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

(All values in million BTU, unless otherwise indicated

| MONTH | TOTAL INCIDENT SOLAR RADIATION (SEA) | TOTAL OPERATIONAL INCIDENT ENERGY (SEOP) | TOTAL ENERGY COLLECTED/ TRANSMITTED (SECA) | OPERATING COLLECTOR TRANSMITTANCE (%) (SEOP_TRANS) | TOTAL ECSS OPERATING ENERGY (SYSOPE) | COLLECTOR LOSS (SG_HL) | COLLECTOR NET GAIN (NET_GAIN) | MOVABLE INSULATION IN PLACE (HOURS/DAY) (MI_TIME) |
|---|---|---|---|---|---|---|---|---|
| MAY | 10.1 | 5.56 | 2.41 | 38 | 0.02 | 1.29 | 1.12 | 9.10 |
| JUN | 9.27 | 4.55 | 1.70 | 41 | 0.07 | 1.09 | 0.61 | 7.83 |
| JUL | 10.7 | 4.19 | 1.74 | 46 | 0.11 | 0.71 | 1.03 | 13.4 |
| TOTAL | 30.1 | 14.3 | 5.85 | - | 0.20 | 3.09 | 2.76 | - |
| AVERAGE | 10.0 | 4.77 | 1.95 | 20 | 0.07 | 1.03 | 0.92 | 10.1 |

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

The performance of the Trombe wall collection subsystem for May 1982 through July 1982 during the cooling season is presented in Table 7.

During the cooling season, the movable insulation was open at night to reject heat collected during the day, and closed during the day to avoid overheating. The Trombe wall collector efficiency was intentionally reduced to nine percent by lowering the movable insulation during the day in the summer, which helped prevent overheating.

Table 7. TROMBE WALL COLLECTION SUBSYSTEM PERFORMANCE, COOLING SEASON

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | INCIDENT SOLAR RADIATION (SEA_TW) | OPERATIONAL INCIDENT SOLAR ENERGY (SEOP_TW) | COLLECTED SOLAR ENERGY (SECA_TW) | NET GAINS (NET_GAIN_TW) | OVERALL COLLECTOR EFFICIENCY (%) (CLEF_TW) |
|---|---|---|---|---|---|
| MAY | 7.31 | 2.73 | 1.70 | 0.96 | 13 |
| JUN | 6.58 | 1.86 | 1.03 | 0.31 | 5 |
| JUL | 7.54 | 1.06 | 0.96 | 0.59 | 8 |
| TOTAL | 21.4 | 5.65 | 3.69 | 1.86 | - |
| AVERAGE | 7.14 | 1.88 | 1.23 | 0.62 | 9 |

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

The performance of the sunspace-greenhouse collection subsystem is presented in Table 8.

During the summer months, the glazing of the sunspace was covered with a metal-decking-type shade device to prevent overheating, and the system was vented through the solar chimney. The maximum temperature in the greenhouse from May through July was 97°F with an average midday temperature of 81°F.

Table 8. SUNSPACE-GREENHOUSE COLLECTION SUBSYSTEM PERFORMANCE, COOLING SEASON

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | INCIDENT SOLAR RADIATION (SEA_SS) | TRANSMITTED SOLAR ENERGY (SECA_SS) | NET GAINS (NET_GAIN_SS) | OVERALL COLLECTOR EFFICIENCY (%) (CLEF_SS) | AVERAGE SUNSPACE TEMP (°F) (SS_TA) | AVERAGE SUNSPACE TEMP AT ± 3 HRS TSN (°F) (SS_TDA) | MAXIMUM SUNSPACE TEMP (°F) (SS_TA_MAX) | AIR-CORE FANS OPERATING ENERGY (CSOPE_FAN) |
|---|---|---|---|---|---|---|---|---|
| MAY | 2.83 | 0.71 | 0.16 | 6 | 74 | 76 | 90 | 0.00 |
| JUN | 2.69 | 0.67 | 0.30 | 11 | 77 | 79 | 93 | 0.05 |
| JUL | 3.13 | 0.78 | 0.44 | 14 | 81 | 85 | 97 | 0.09 |
| TOTAL | 8.65 | 2.16 | 0.90 | - | - | - | - | 0.14 |
| AVERAGE/ MAXIMUM | 2.88 | 0.72 | 0.30 | 10 | 77 | 81 | 97 | 0.05 |

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

## 2.2 STORAGE SUBSYSTEM

The storage subsystem consists of three sections of concrete masonry mass: Trombe wall, rear air-core mass wall, and a central mass wall with fireplaces and flues in it. The total mass is 264,000 pounds of concrete masonry. This mass is used for storing solar heat in winter and as a heat sink in the summer for summer cooling.

### Heating Performance

The performance of the storage subsystem is presented in Table 9 for three months of the heating season.

The total energy delivered to the storage subsystem was 15.0 million BTU. This represents 90% of the total solar energy collected by the glazing system. The storage subsystem delivered 14.3 million BTU to the space heating load, or 86% of the collected solar energy.

The average storage temperature (64°F) was the same as the average building temperature during the heating season.

Table 9. STORAGE PERFORMANCE, HEATING SEASON

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | ENERGY TO STORAGE (STEI) | ENERGY FROM STORAGE (STEO) | CHANGE IN STORED ENERGY (STECH) | AVERAGE STORAGE TEMPERATURE (°F) (TST) | AVERAGE BUILDING TEMPERATURE (°F) (TB) |
|---|---|---|---|---|---|
| FEB | 4.95 | 4.59 | 0.36 | 62 | 62 |
| MAR | 5.11 | 5.00 | 0.12 | 63 | 63 |
| APR | 4.93 | 4.70 | 0.23 | 67 | 68 |
| TOTAL | 15.0 | 14.3 | 0.70 | - | - |
| AVERAGE | 5.00 | 4.76 | 0.23 | 64 | 64 |

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

Figure 4 shows a plot of three typical winter days' performance. The plot covers February 26 through February 28, 1982. The plot shows data for solar energy, black bulb temperature (mean radiant temperature) of the building, storage temperature, outdoor ambient temperature, and electrical energy consumption of the electric baseboard heaters.

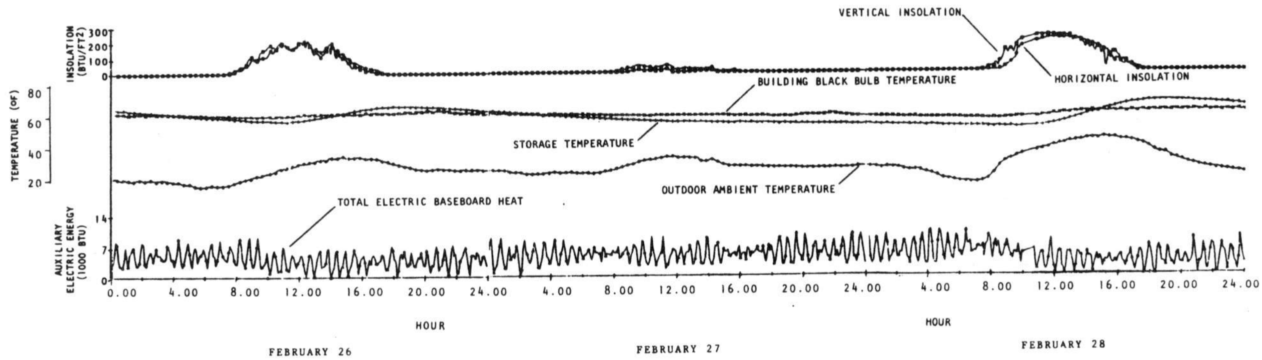



Figure 4. Typical Heating Season Performance
Roberts Home
February 26, 27, and 28, 1982

February 26 was a good solar day with 1,063 BTU/ft$^2$ of solar energy available. The building temperature at the beginning of the day was 60°F, and rose to 64°F by 5:00 p.m. The lowest storage temperature was 61°F at 12:00 noon; the highest was 65°F at 5:00 p.m. During this period, the ambient temperature ranged from 18°F to 38°F. February 27 had very little solar energy available (50 BTU/ft$^2$) and the ambient temperature ranged from 25°F to 36°F. The storage temperature went from 60°F at 12:00 noon to 57°F that night. The building temperature ranged from 61°F to 59°F.

February 28 was an excellent solar day with 1,373 BTU/ft$^2$ of solar energy available and the ambient temperature ranged from 19°F to 48°F. The storage temperature rose from a low of 56°F in the morning to a high of 66°F by 6:00 p.m. The building temperature ranged from 58°F to 64°F.

## Cooling Performance

The performance of the storage subsystem for three months of the cooling season is presented in Table 10.

During the summer months, the movable insulation was closed during the day to prevent heat gain and opened at night to radiate heat to the night sky. The vents in the thermal chimney were opened to bring cool night air through the earth tubes, over the Trombe wall and out the vents. This helped keep the mass wall cool.

## Table 10. STORAGE PERFORMANCE, COOLING SEASON

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | ENERGY TO STORAGE (STEI) | ENERGY FROM STORAGE (STEO) | CHANGE IN STORED ENERGY (SECA) | AVERAGE STORAGE TEMPERATURE (°F) (TST) | AVERAGE BUILDING TEMPERATURE (°F) (TB) |
|---|---|---|---|---|---|
| MAY | 3.58 | 3.16 | 0.42 | 70 | 72 |
| JUN | 3.20 | 3.08 | 0.12 | 72 | 73 |
| JUL | 3.06 | 2.89 | 0.17 | 76 | 77 |
| TOTAL | 9.84 | 9.13 | 0.71 | - | - |
| AVERAGE | 3.28 | 3.04 | 0.24 | 73 | 74 |

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

The storage subsystem gained 9.84 million BTU from the solar glazing, and released 9.13 million BTU. A large part of these gains, 3.99 million BTU, were vented out of the thermal chimney. The balance, 5.20 million BTU, contributed to the cooling load. The storage temperature increased from 70°F in May to 76°F in July. The average storage temperature was generally lower than the building temperature, thus acting as an effective heat sink and increasing comfort.

Figure 5 shows a plot of the storage subsystem performance for three typical summer days, July 14, 15, and 16, 1982.

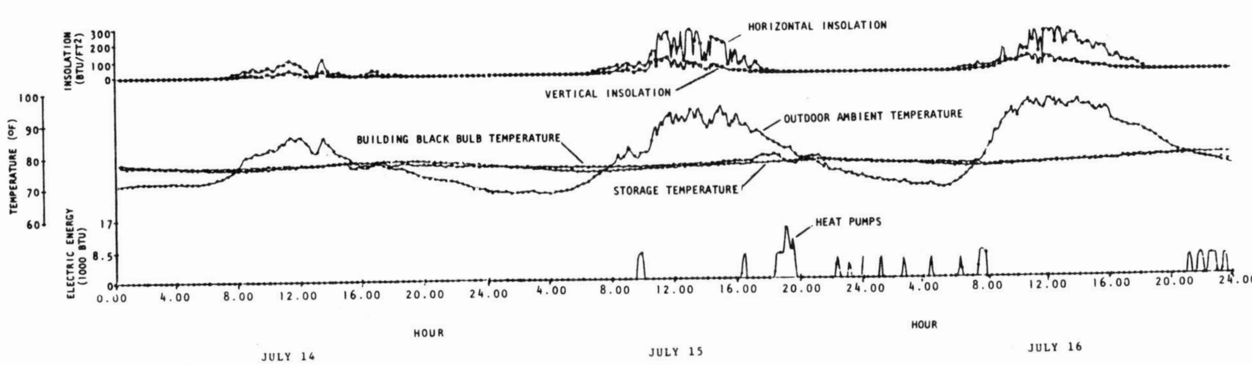



Figure 5. Typical Cooling Season Performance
Roberts Home
July 14, 15, and 16, 1982

July 14 was a hot cloudy day and the ambient temperature went from 69°F to 84°F. The storage temperature that day ranged from 77°F to 78°F. The building temperature was from 77°F to 79°F. The heat pumps did not operate on this day.

July 15 and July 16 were sunny and hot summer days. The ambient temperature on July 15 went from 67°F to 90°F, and on July 16 the ambient temperature went from 68°F to 93°F. The storage temperature ranged from 76°F in the early morning to 77°F in the late afternoon on July 15, and from 76°F to 78°F in the late afternoon on July 16. During the same period, the building temperature went from 75°F to 79°F on July 15, and from 76°F to 80°F on July 16. The heat pump only ran for short periods during this time.

## 2.3 SPACE HEATING SUBSYSTEM

The space heating subsystem performance for three months of the heating season, February 1982 through April 1982, is shown in Table 11.

Table 11. SPACE HEATING SUBSYSTEM

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

(All values in million BTU, unless otherwise indicated)

| MONTH | BUILDING HEAT LOAD (BL) | SOLAR ENERGY USED (HSEP) | BUILDING SOLAR FRACTION (%) (BHSFR) | INTERNAL GAINS (HOTHER) | FIREPLACES (HFIRE) | AUXILIARY ELECTRIC (HAE) | OPERATING ENERGY (SYSOPE) | BUILDING TEMP (°F) (TB) | AMBIENT TEMP (°F) (TA) | HEATING DEGREE-DAYS (#) (HDD) |
|---|---|---|---|---|---|---|---|---|---|---|
| FEB | 11.2 | 5.11 | 46 | 3.64 | 0.31 | 2.12 | 0.17 | 62 | 38 | 729 |
| MAR | 10.5 | 5.24 | 50 | 4.07 | 0.54 | 0.61 | 0.25 | 63 | 43 | 649 |
| APR | 8.7 | 5.54 | 64 | 3.14 | 0.00 | 0.00 | 0.06 | 68 | 52 | 395 |
| TOTAL | 30.4 | 15.9 | - | 10.9 | 0.85 | 2.73 | 0.48 | - | - | 1,773 |
| AVERAGE | 10.1 | 5.30 | 52 | 3.62 | 0.28 | 0.91 | 0.16 | 64 | 44 | 591 |

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

The space heating subsystem at the Roberts Home consists of electric baseboard heaters and fireplaces as well as the passive solar system. The total building heat load of 30.4 million BTU was met by nine percent auxiliary electric baseboard heat, or 799 kwh. This represents $48 worth of auxiliary electric heat for the three-month period from February through April, or $16. per month.

The fireplaces were used occasionally in February and March and contributed approximately 0.85 million BTU to the building load. This represents about one-third a cord of hardwood based on 25 million BTU per cord and approximately 10% efficiency of the fireplace.

The majority of the space heating was provided by the radiant heat transfer from the Trombe wall and rear air-core mass wall. Ninety percent (14.3 million BTU) of the solar energy used was delivered from storage. Therefore, the storage subsystem provided 47% of the building heating requirements. Internal gains also provided a significant portion of the building heat load (36%).

The average building space heating load ($UA\Delta T$ + infiltration) was 7.44 BTU/degree-day/ft$^2$ based on a 65°F degree-day base. This heating load is high for a well-insulated building. However, the heating load would be 3.54 BTU/degree-day/ft$^2$ if only the auxiliary energy and internal gains (purchased energy or nonsolar energy used) required to maintain the building were counted.

For comparison purposes, the NSDN monitored a new nonsolar well-insulated house (Rymark I) in the same geographical area. The nonsolar Rymark I space heating load was 4.64 BTU/degree-day/ft$^2$ during the heating season.

Table 12 shows the passive system environmental conditions for February 1982 through April 1982. The average building temperature was 64°F with a maximum of 76°F and a minimum of 56°F. The indoor relative humidity was a low 25%. The average storage temperature was the same as the building temperature of 64°F, while the average ambient temperature was 44°F. The average ambient temperature during the day was 52°F and there were 48.2 million BTU of solar energy available.

Table 12. PASSIVE SYSTEM ENVIRONMENT, HEATING SEASON

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

| MONTH | BUILDING TEMPERATURE (°F) (TB) | MAXIMUM BUILDING TEMPERATURE (°F) (TB_MAX) | MINIMUM BUILDING TEMPERATURE (°F) (TB_MIN) | INDOOR RELATIVE HUMIDITY (%) (RHIN) | AVERAGE STORAGE TEMPERATURE (°F) (TST) | AMBIENT TEMPERATURE (°F) (TA) | DAYTIME AMBIENT TEMPERATURE (°F) (TDA) | TOTAL INCIDENT SOLAR RADIATION (Million BTU) (SEA) |
|---|---|---|---|---|---|---|---|---|
| FEB | 62 | 69 | 57 | 25 | 62 | 38 | 44 | 15.3 |
| MAR | 63 | 71 | 56 | 27 | 63 | 43 | 50 | 15.0 |
| APR | 68 | 76 | 57 | 22 | 67 | 52 | 61 | 17.9 |
| TOTAL | - | - | - | - | - | - | - | 48.2 |
| AVERAGE/ MAX/MIN | 64 | 76 | 56 | 25 | 64 | 44 | 52 | 16.1 |

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

The month by month performance of the Roberts Home is presented graphically in Figures 6, 7, and 8 for the three months of the heating season, February 1982 through April 1982. The graphs present average daily temperatures and total solar and auxiliary energy.

Data collection began on February 12, 1982. During the rest of the month, the ambient temperatures ranged from a low of 16°F on February 14 to a high of 69°F on February 16, and the minimum building temperature was 57°F on February 13 and 28. The highest auxiliary energy use occurred on February 14 and the lowest occurred on February 16. The average solar energy available was 678 BTU/ft$^2$-day with a maximum of 1,424 BTU/ft$^2$-day on February 25 and a low of three BTU/ft$^2$-day on February 17.

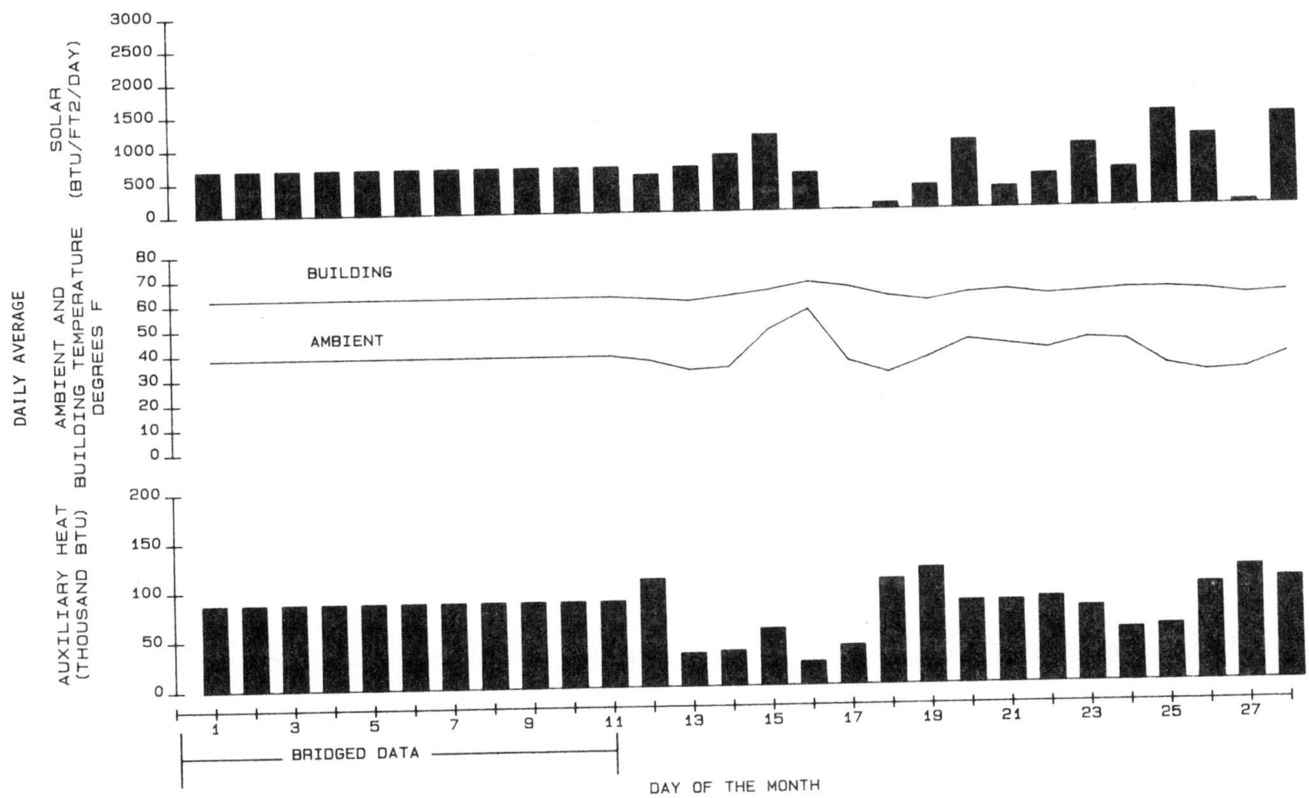



Figure 6. Building Performance
Roberts Home
February 1982

During March, the building temperature fluctuated from a low of 56°F on March 11 to a high of 71°F on March 25. The ambient temperature went from a low of 31°F on March 8 to a high of 57°F on March 31. The greatest amount of auxiliary energy was used on March 7. There were 16 days in March when no auxiliary energy was used. The solar energy available at the site averaged 596 BTU/ft$^2$-day with a high of 1,199 BTU/ft$^2$-day on March 9 and a low of 16 BTU/ft$^2$-day on March 7.

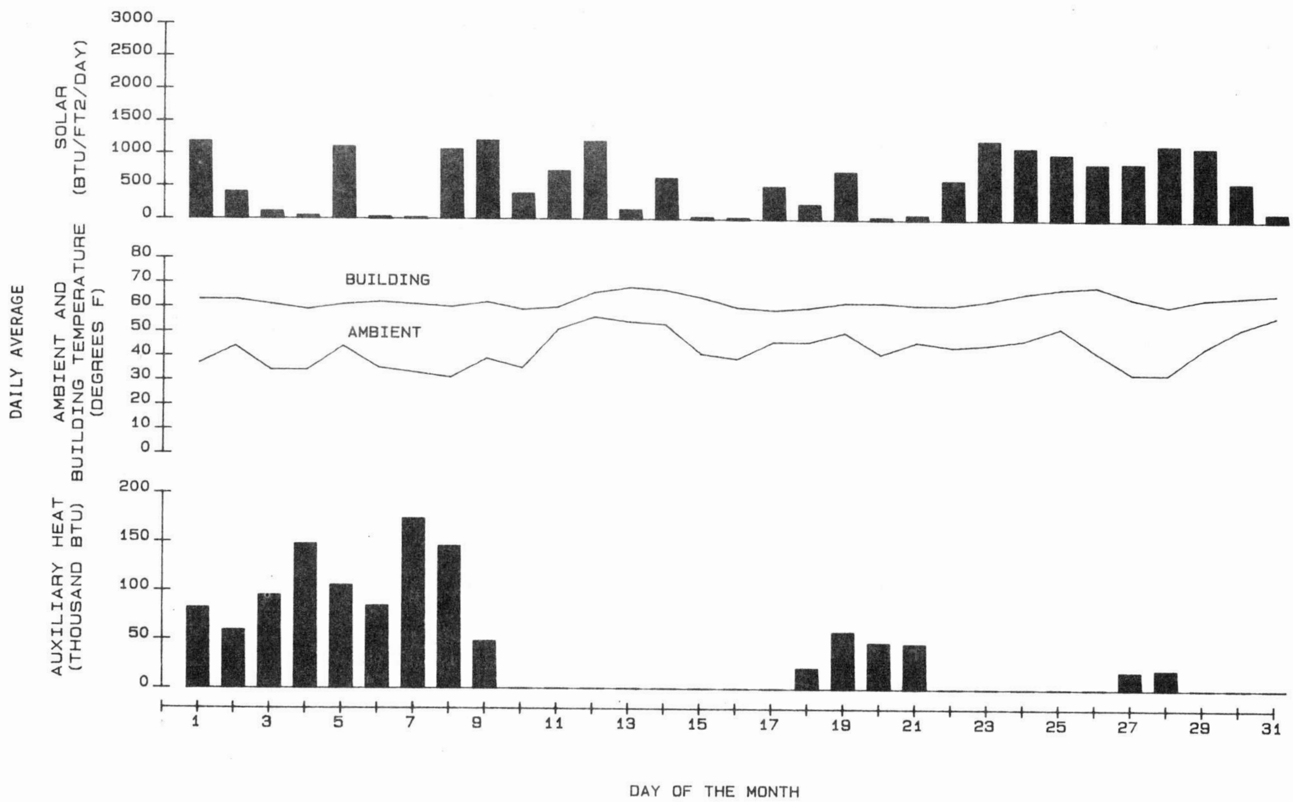



Figure 7. Building Performance
Roberts Home
March 1982

April was a mild month with ambient temperatures ranging from 82°F on April 17 and April 25 to 22°F on April 7. The average ambient temperature was only 52°F for the month. The building temperature ranged from 76°F on April 17 to 57°F on April 7, 8, and 10. No auxiliary heat was used this month. The average solar input was 686 BTU/ft$^2$-day with a high of 1,083 BTU/ft$^2$-day on April 1 and a low of 45 BTU/ft$^2$-day on April 26.

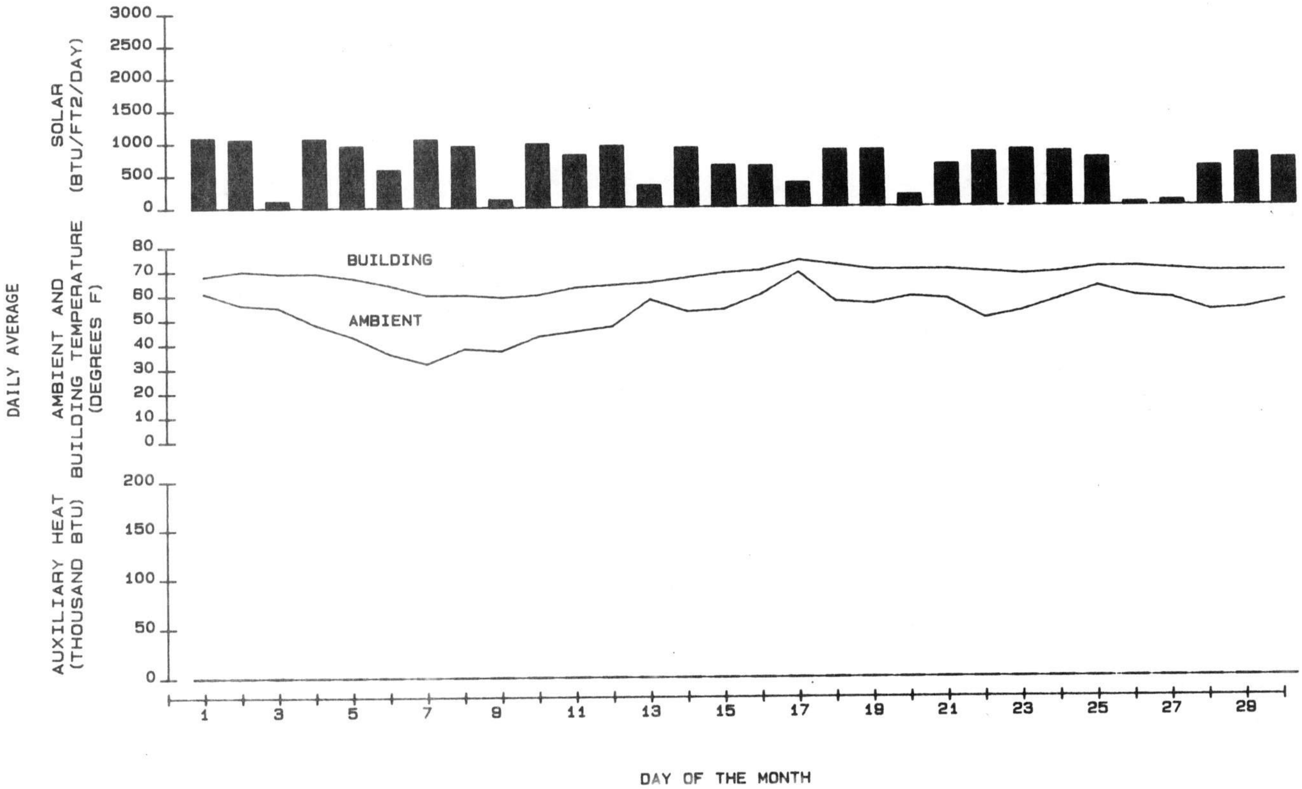



Figure 8. Building Performance
Roberts Home
April 1982

## 2.4 PASSIVE COOLING SUBSYSTEM

The passive cooling subsystem performance for three months of the cooling season, May 1982 through July 1982, is shown in Table 2 on Page 4.

The performance of the passive cooling subsystem was good for this period. The cooling load was 24.8 million BTU with 719 cooling degree-days. Several elements comprise the cooling load: internal gains, solar gains through the glazing, solar gains through the building envelope, and the heat pump compressor power. The solar gains through the building envelope (radiant cooling load) were the greatest portion of the cooling load, representing 12.4 million BTU. The next greatest component of the cooling load was the internal gains, which were 7.13 million BTU. The net solar gains through the glazing were 5.20 million BTU. The shading system on the greenhouse and the Trombe wall movable insulation effectively avoided 24.8 million BTU of solar gain.

The heat pump compressor power of 0.07 million BTU is the final component of the total building cooling load of 24.8 million BTU.

The cooling load at the Roberts Home was offset by three factors: conduction through the building envelope when outside temperatures were below inside temperatures, auxiliary cooling from the heat pumps, and passive cooling through ventilation. The passive cooling ventilation system consists of windows, two thermal chimneys which draw cool air in through open windows and tubes buried in the ground. The tubes are used primarily to cool the Trombe wall.

The conduction losses through the building envelope were 3.57 million BTU or 14% of the cooling load. The passive cooling system dissipated 21.2 million BTU or 85% of the cooling load. The heat pumps removed 0.07 million BTU or less than one percent of the total cooling load. Therefore, it can be said that the Roberts Home was better than 99% cooled by passive elements designed into the building.

Table 13 shows the passive system environmental conditions for the period from May 1982 through July 1982. The average building temperature was 74°F with a maximum of 82°F and a minimum of 63°F. The indoor relative humidity averaged 51%. The average storage temperature of 73°F was very close to the building temperature. The average ambient temperature was 71°F with a daytime average of 78 °F. There were 30.1 million BTU of solar energy available during this three-month period.

Table 13. PASSIVE SYSTEM ENVIRONMENT, COOLING SEASON

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

| MONTH | BUILDING TEMPERATURE (°F) (TB) | MAXIMUM BUILDING TEMPERATURE (°F) (TB_MAX) | MINIMUM BUILDING TEMPERATURE (°F) (TB_MIN) | INDOOR RELATIVE HUMIDITY (%) (RHIN) | AVERAGE STORAGE TEMPERATURE (°F) (TST) | AMBIENT TEMPERATURE (°F) (TA) | DAYTIME AMBIENT TEMPERATURE (°F) (TDA) | TOTAL INCIDENT SOLAR RADIATION (Million BTU) (SEA) |
|---|---|---|---|---|---|---|---|---|
| MAY | 72 | 76 | 63 | 41 | 70 | 66 | 73 | 10.1 |
| JUN | 73 | 80 | 64 | 54 | 72 | 70 | 76 | 9.3 |
| JUL | 77 | 82 | 66 | 57 | 76 | 76 | 85 | 10.7 |
| TOTAL | - | - | - | - | - | - | - | 30.1 |
| AVERAGE/MAX/MIN | 74 | 82 | 63 | 51 | 73 | 71 | 78 | 10.0 |

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

The month by month performance of the Roberts Home for three months of the cooling season is presented graphically in Figures 9, 10 and 11. The values plotted are average daily temperatures and daily total solar and auxiliary energy.

May was a transition month with both heating and cooling loads. The ambient temperatures ranged from a high of 91°F on May 12 to a low of 40°F on May 5. The building temperature ranged from a maximum of 76°F on May 18, 19, 20, 21 and 29 to a minimum of 63°F on May 10. There was no auxiliary heating or cooling required this month.

The trees on the site shade the building quite well and the average insolation on the glazing in May was 391 BTU/ft$^2$-day with a maximum of 720 BTU/ft$^2$-day and a minimum of 17 BTU/ft$^2$-day. Problems with the data collection system prevented the collection of data from May 6 through May 17. Therefore, the values shown on the graph for this period are monthly average values.

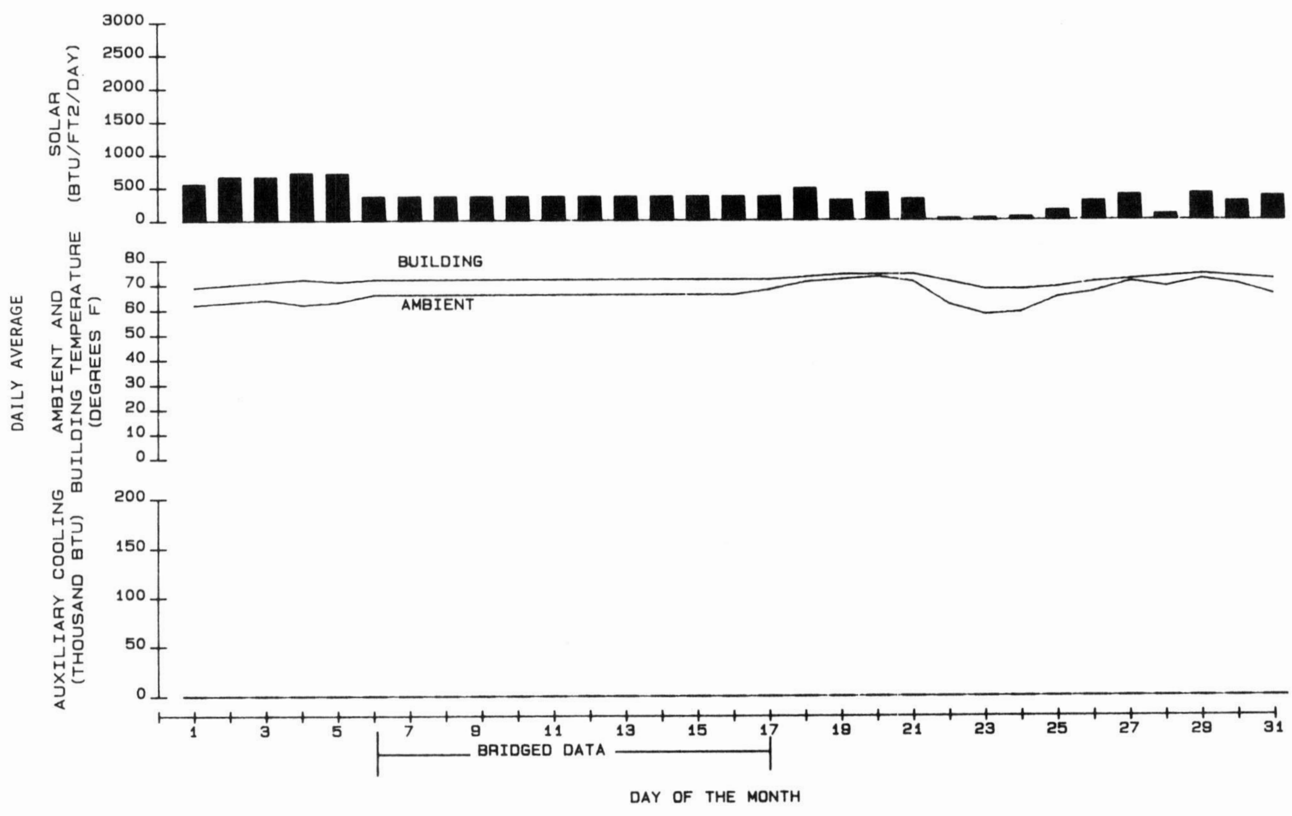



Figure 9. Building Performance
Roberts Home
May 1982

During June, the ambient temperatures fluctuated from a high of 90°F on June 28 to a low of 61°F on June 12. The building maintained a comfortable 73°F with a maximum of 80°F on June 28 and 29 and a minimum of 64°F on June 24.

There was no auxiliary cooling energy used in June. The trees continued to shade the building, with an average insolation of only 327 BTU/ft$^2$-day. The maximum was 527 BTU/ft$^2$-day on June 27 and the minimum was 16 BTU/ft$^2$-day on June 10. Monthly average values are shown for this period on the graph.

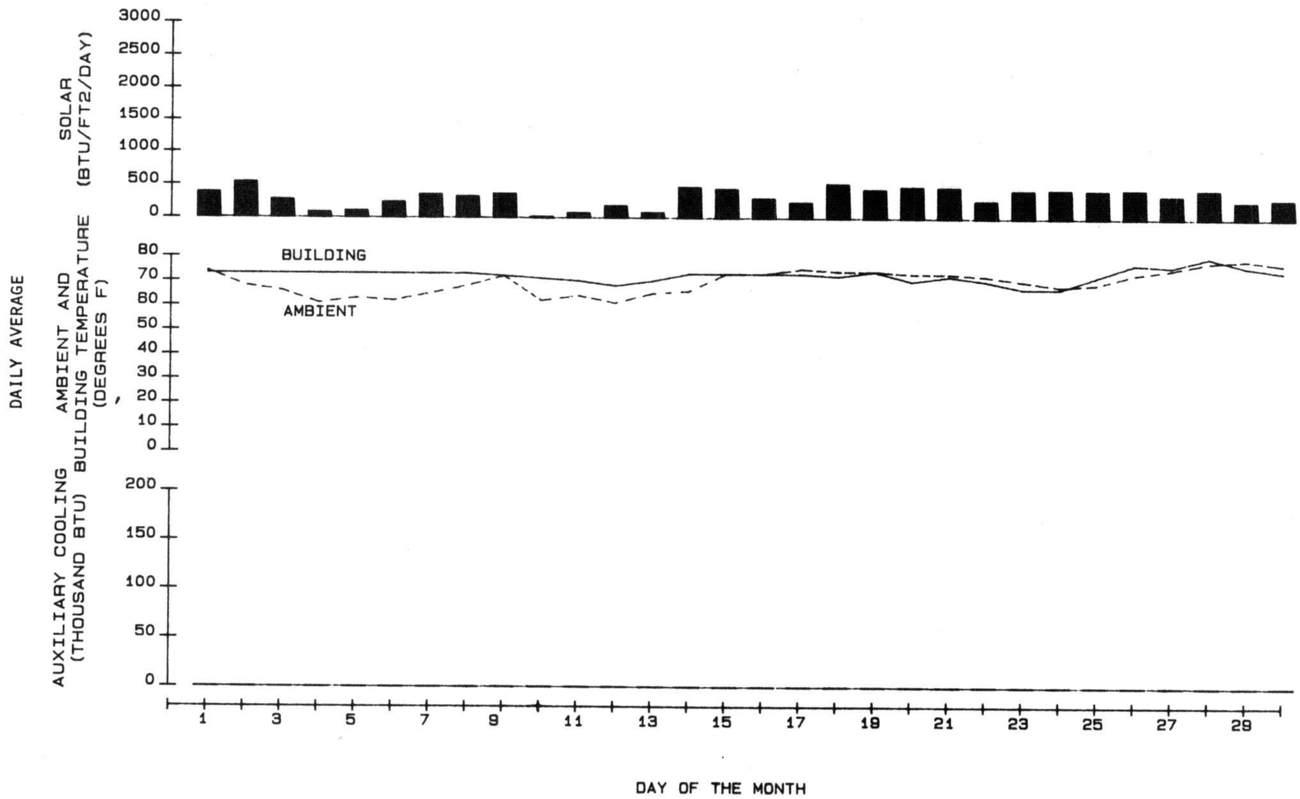



Figure 10. Building Performance
Roberts Home
June 1982

July temperatures reached 96°F on July 18. The lowest ambient temperature was 54°F on July 2. The average ambient temperature for the month was 76°F. During this period, the building temperature was an average of 77°F with a maximum of 82°F on July 17, 18, and 19 and a minimum of 66°F on July 7.

Auxiliary cooling energy was used from July 15 through July 18. During this period, the ambient temperature reached a high of 90°F to 96°F.

The data shown on the graph for the period from July 22 through the end of the month are average values due to data collection problems.

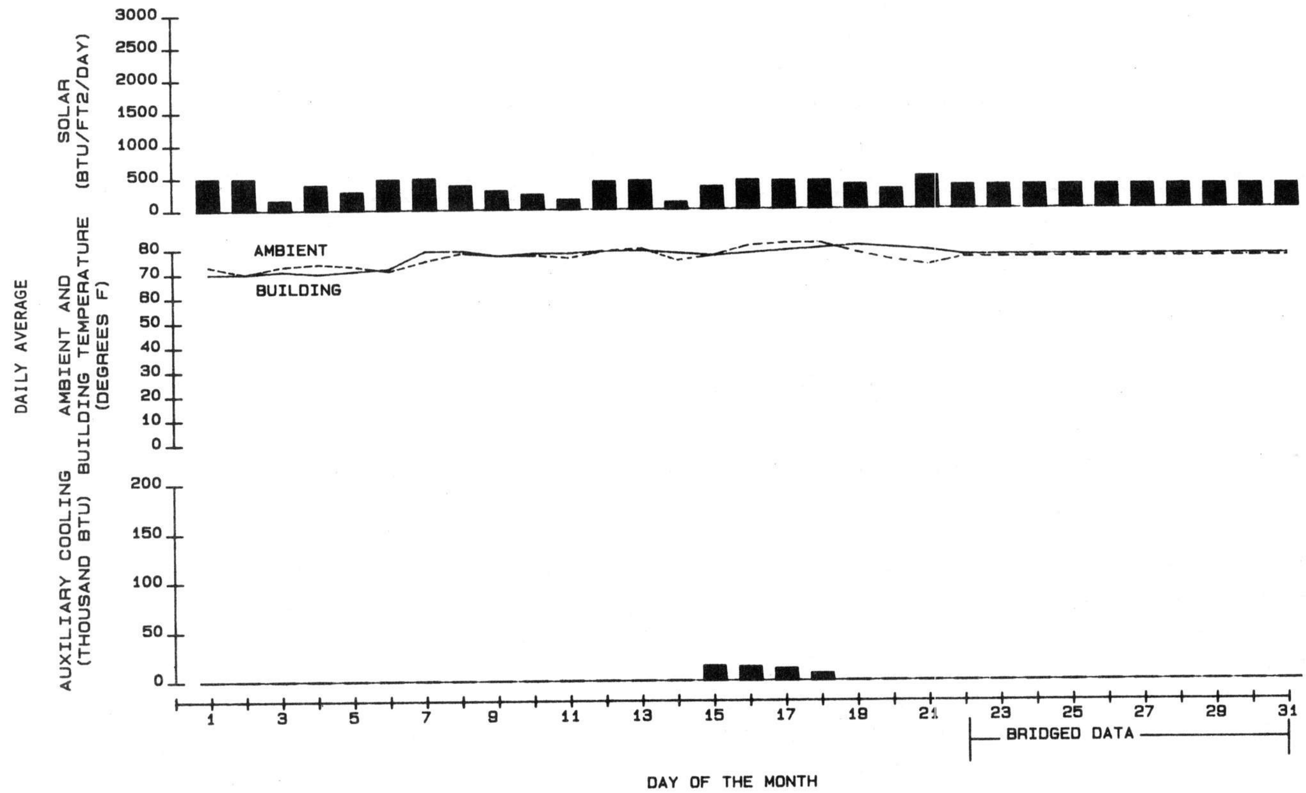



Figure 11. Building Performance
Roberts Home
July 1982

An important factor to consider in evaluating a passive cooling system is occupant comfort. The comfort level for cooling, defined according to the ASHRAE Thermal Comfort Index (Reference 9), assumes that if the environmental conditions are within a given range of temperature and humidity, then the occupants will be comfortable. The outside limits for comfort are 72°F to 77°F and 20% to 60% relative humidity. The number of hours during the monitoring period when indoor temperature and relative humidity were within the ASHRAE Thermal Comfort Index is shown in Table 14.

During the three months of the cooling season, 893 cooling hours were measured out of 1,363 hours that were monitored. Indoors, it was comfortable (ASHRAE method) for 707 of these hours, while outdoors it was only comfortable for 98 of these hours. About 62% of the total clock hours were used in the comfort analysis. The actual comfortable hours were greater than 707 because many hours fell below the 72°F bottom ASHRAE limit.

Table 14. ASHRAE THERMAL COMFORT INDEX (HOURLY)

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

| MONTH | OUTDOOR COMFORT HOURS (OCH) | INDOOR COMFORT HOURS (ICH) | TOTAL DATA HOURS USED |
|---|---|---|---|
| MAY | 29 | 301 | 432 |
| JUN | 50 | 257 | 437 |
| JUL | 19 | 149 | 494 |
| TOTAL | 98 | 707 | 1,363 |

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

The thermal chimneys were quite effective in cooling the Roberts Home. The thermal chimneys have the capacity to remove approximately 23,300 BTU per hour at an 8°F difference in temperature from inside to outdoors. The thermal chimneys induced flow during the day via the cooling tubes. At night the flow was mostly through open windows. The windows were opened from about 7:00 p.m. to between 6:00 a.m. and 8:00 a.m. The house was usually closed up during the day when the night-cooled mass absorbed the solar and internal gains. There were only a few days of uncomfortable indoor temperatures in July - during a period when the occupants were out of town. While gone, they closed all the windows and positioned the thermal curtain in the down position. Both storage and building temperatures rose, due to the lack of night-cooling ventilation. Interior relative humidity decreased, most likely due to the reduction of water vapor produced by showers, cooking, and the occupants, and to the higher indoor temperatures.

The storage subsystem played a significant role in the performance of the passive cooling system. The large storage mass in the building worked very well in reducing overheating and improving comfort in the cooling season. The storage mass was kept at a cool 73°F by the cooling tubes, movable insulation, and thermal chimneys. The mass wall also has an apparent effect on the humidity levels in the building. From April through July, the indoor relative humidity rose from a 22% average to a 57% average, while the outdoor relative humidity rose from a 43% average in April to a mid 70% by the end of July. The passive system masonry storage unit also reduced humidity swings indoors.

# SECTION 3

# OPERATING ENERGY, ENERGY SAVINGS AND WEATHER CONDITIONS

## 3.1 OPERATING ENERGY

Table 15 presents the operating energy which was used for the three months of the heating season from February 1982 through April 1982. The fans that pull air through the Trombe wall and push it down the rear air-core mass wall consumed 0.42 million BTU or 123 kwh of electricity. This is $7.38 worth of electricity based on a cost of $0.06 per kwh. The motorized insulating curtain used 0.06 million BTU or 18 kwh. This is just over $1.00 for the three-month period. The total operating energy for the three-month period was 0.48 million BTU or 141 kwh, representing a total cost of $8.46 for the three months.

Table 15. SOLAR OPERATING ENERGY, HEATING SEASON

ROBERTS HOME
FEBURARY 1982 THROUGH APRIL 1982

(All values in million BTU)

| MONTH | AIR-CORE FANS OPERATING ENERGY (CSOPE_FAN) | INSULATING CURTAIN OPERATING ENERGY (CSOPE_CUR) | TOTAL SOLAR OPERATING ENERGY (SYSOPE) |
|---|---|---|---|
| FEB | 0.15 | 0.02 | 0.17 |
| MAR | 0.23 | 0.02 | 0.25 |
| APR | 0.04 | 0.02 | 0.06 |
| TOTAL | 0.42 | 0.06 | 0.48 |
| AVERAGE | 0.14 | 0.02 | 0.16 |

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

Table 16 presents the operating energy which was used for the three months of the cooling season from May 1982 through July 1982. Oscillating fans were used in the house to improve comfort during the cooling season. The oscillating fans consumed 2.21 million BTU or 647 kwh of electricity. This is $38.82 at $0.06 per kwh for the three-month period. The air-core fans used 0.14 million BTU or 41 kwh, and the motor on the movable insulation used 0.06 million BTU or 18 kwh. The total operating energy for the three months of the cooling season was 2.41 million BTU or 706 kwh. This is $42.36 worth of electricity.

## Table 16. SOLAR OPERATING ENERGY, COOLING SEASON

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

(All values in million BTU)

| MONTH | OSCILLATING FAN OPERATING ENERGY (COPE_FAN) | AIR-CORE FAN OPERATING ENERGY (CSOPE_FAN) | INSULATING CURTAIN OPERATING ENERGY (CSOPE_CUR) | TOTAL SOLAR OPERATING ENERGY (SYSOPE) |
|---|---|---|---|---|
| MAY | 0.71 | 0.00 | 0.02 | 0.73 |
| JUN | 0.69 | 0.05 | 0.02 | 0.76 |
| JUL | 0.81 | 0.09 | 0.02 | 0.92 |
| TOTAL | 2.21 | 0.14 | 0.06 | 2.41 |
| AVERAGE | 0.74 | 0.05 | 0.02 | 0.80 |

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

## 3.2 ENERGY SAVINGS

The net energy savings for the Roberts Home are shown in Table 17 for February 1982 through April 1982, and in Table 18 for May 1982 through July 1982. The net energy savings in space heating energy were 15.4 million BTU or 4,512 kwh. This represents a savings of $271 based on a cost of $0.06 per kwh. The net cooling energy savings were 20.5 million BTU. If the Roberts Home had used a typical air-conditioning system with an average COP of 2.5, then the energy savings for cooling would be 2,407 kwh or $144 for the three-month period.

## Table 17. ENERGY SAVINGS, HEATING SEASON

ROBERTS HOME
FEBRUARY 1982 through APRIL 1982

(All values in million BTU)

| MONTH | SOLAR ENERGY USED (HSEP) | SPACE HEATING ELECTRICAL (HAE) | AIR-CORE MASS WALL FANS (CSOPE_FAN) | AUTOMATED THERMAL CURTAIN OPERATING ENERGY (CSOPE_CUR) | TOTAL OPERATING ENERGY SOLAR-UNIQUE (SYSOPE) | NET ENERGY SAVINGS ELECTRICAL (TSVE) |
|---|---|---|---|---|---|---|
| FEB | 5.11 | 5.11 | 0.15 | 0.02 | 0.17 | 4.95 |
| MAR | 5.24 | 5.24 | 0.23 | 0.02 | 0.25 | 4.99 |
| APR | 5.54 | 5.54 | 0.04 | 0.02 | 0.06 | 5.47 |
| TOTAL | 15.9 | 15.9 | 0.42 | 0.06 | 0.48 | 15.4 |
| AVERAGE | 5.30 | 5.30 | 0.14 | 0.02 | 0.16 | 5.14 |

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

## Table 18. ENERGY SAVINGS, COOLING SEASON

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

(All values in million BTU)

| MONTH | SOLAR ENERGY USED | SPACE CONDITIONING ELECTRICAL | COOLING OSCILLATING FANS POWER | MANUALLY OPERATED AIR-CORE MASS WALL FANS | AUTOMATED THERMAL CURTAIN OPERATING ENERGY | TOTAL OPERATING ENERGY SOLAR-UNIQUE | NET ENERGY SAVINGS ELECTRICAL |
|---|---|---|---|---|---|---|---|
| | (CSEP) | (CAE) | (COPE_FAN) | (CSOPE_FAN) | (CSOPE_CUR) | (SYSOPE) | (CTSVE) |
| MAY | 6.94 | 6.94 | 0.71 | 0.00 | 0.02 | 0.73 | 6.21 |
| JUN | 6.39E | 6.39 | 0.69 | 0.05 | 0.02 | 0.76 | 5.63 |
| JUL | 9.62 | 9.62 | 0.81 | 0.09 | 0.02 | 0.92 | 8.70 |
| TOTAL | 23.0 | 23.0 | 2.21 | 0.14 | 0.06 | 2.39 | 20.5 |
| AVERAGE | 7.65 | 7.65 | 0.74 | 0.05 | 0.02 | 0.80 | 6.85 |

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

## 3.3 WEATHER CONDITIONS

The weather conditions for Northern Virginia for the reporting period, February 1982 through July 1982, compared to the long-term averages, are presented in Table 19.

## Table 19. WEATHER CONDITIONS

ROBERTS HOME
FEBRUARY 1982 THROUGH JULY 1982

| MONTH | DAILY INCIDENT SOLAR ENERGY PER UNIT AREA ($BTU/FT^2$-DAY) MEASURED | DAILY INCIDENT SOLAR ENERGY LONG-TERM AVERAGE* | AMBIENT TEMPERATURE (°F) MEASURED | AMBIENT TEMPERATURE (°F) LONG-TERM AVERAGE* | HEATING/COOLING DEGREE-DAYS MEASURED HEATING | MEASURED COOLING | LONG-TERM AVERAGE* HEATING | LONG-TERM AVERAGE* COOLING |
|---|---|---|---|---|---|---|---|---|
| | (SE) | | (TA) | | (HDD) | (CDD) | | |
| FEB | 678 | 962 | 38 | 34 | 729 | 0 | 874 | 0 |
| MAR | 596 | 949 | 43 | 42 | 649 | 0 | 719 | 0 |
| APR | 686 | 850 | 52 | 53 | 395 | 0 | 367 | 0 |
| MAY | 391 | 755 | 66 | 63 | 45 | 125 | 131 | 57 |
| JUN | 327 | 729 | 70 | 71 | 0 | 217 | 0 | 188 |
| JUL | 366 | 740 | 76 | 75 | 0 | 377 | 0 | 319 |
| TOTAL | - | - | - | - | 1,818 | 719 | 2,091 | 564 |
| AVERAGE | 507 | 831 | 58 | 56 | 454 | 240 | 523 | 188 |

* Long-term average data from Appendix D.

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

The measured solar energy on the vertical south wall averaged 507 BTU/$ft^2$-day as compared to an expected long-term average of 831 BTU/$ft^2$-day. The measured value was much lower than expected due in part to shading by trees to the south of the building. The average temperature for the period was 58°F as compared to a long-term average of 56°F. The measured Heating Degree-Days (HDD) were 1,818 HDD as compared to the long-term average of 2,091 HDD. The Cooling Degree-Days (CDD) were 719 CDD compared to 564 CDD long-term average.

## SECTION 4

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

*5A. User's Guide to Monthly Performance Reports, November 1981, SOLAR/0004-81/18, Vitro Laboratories, Silver Spring, Maryland.

*5B. Instrumentation Installation Guidelines, March 1981, Parts 1, 2, and 3, SOLAR/0001-81/15, Vitro Laboratories, Silver Spring, Maryland.

6. Monthly Performance Report, Roberts Home, February 1982, Vitro Laboratories, Silver Spring, Maryland.

7. Monthly Performance Report, Roberts Home, March 1982, Vitro Laboratories, Silver Spring, Maryland.

8. Monthly Performance Report, Roberts Home, April 1982, Vitro Laboratories, Silver Spring, Maryland.

9. ASHRAE Handbook & Product Directory: 1977 Fundamentals, The American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, N.Y., 1977.

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

# APPENDIX A

## SYSTEM DESCRIPTION

# APPENDIX A-1

## SYSTEM DESCRIPTION

The Roberts Home is a three-story 2,300-square-foot single family residence located in Reston, Virginia. The home has a passive solar space heating system and a passive cooling system consisting of the following elements:

- Vented Trombe wall with an automated movable insulation system
- Sunspace located on the third floor
- Fan-forced air-core mass wall
- Earth tubes
- Thermal chimneys

The building's passive heating and cooling system is shown schematically in Figures A-1 through A-6.

The Trombe wall consists of 663 square feet of single Plexiglass® glazing. The Trombe wall is insulated at night during the winter with an automated R-12 movable insulation system manufactured by Thermal Technology Corporation. The operation of the insulation is controlled by a differential thermostat which opens the insulation only when there is a net gain across the glazing. During the summer, the reflective movable insulation is closed during the day to prevent overheating of the Trombe wall and opened at night to reject heat from the Trombe wall.

A sunspace is located on the third floor and incorporates 99 square feet of double glass glazing tilted 48 degrees from the horizontal. The sunspace does not use movable insulation. During the summer months, the sunspace glazing is shaded on the outside with a roll-down shading device.

The heat collected by the Trombe wall and the sunspace is blown through the rear air-core mass wall, under the floor, and back through the Trombe wall by the use of four small fans located at the top of the rear air-core mass wall. Two of the fans vent the east Trombe wall and the sunspace into the rear air-core mass wall, and the other two fans vent the west Trombe wall into the rear air-core mass wall.

Solar heat is delivered to the living space primarily by radiation from the Trombe wall and the rear air-core mass wall. Backup space heating is provided by electric baseboard heaters and the fireplaces.

Passive cooling is provided by two thermal chimneys located at the east and west ends of the building that draw air from cooling tubes buried in the earth, through the air space between the

Trombe wall and the glazing and out through the thermal chimney. This cooling is all done passively by thermal convection. The windows of the home are also used for ventilation in the summer. Heat is rejected from the Trombe wall on cool nights by opening the insulating curtain. This is an automatic operation when ambient temperature is below 75°F. Auxiliary cooling is provided by ceiling fans and oscillating fans located throughout the house and three independent through-the-wall mounted heat pumps.

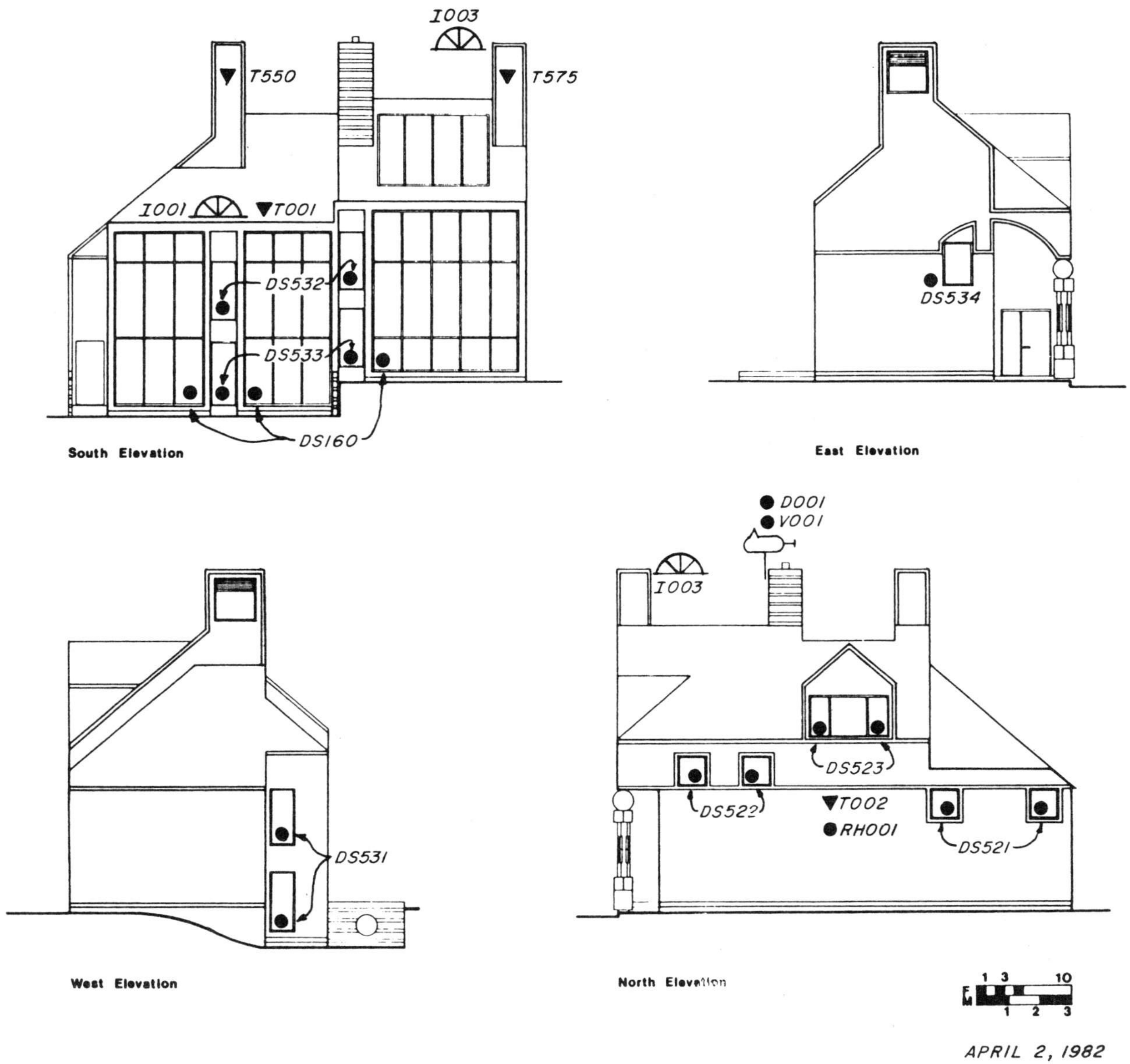



Figure A-1. Roberts Home Passive Solar Energy System Schematic, Elevations

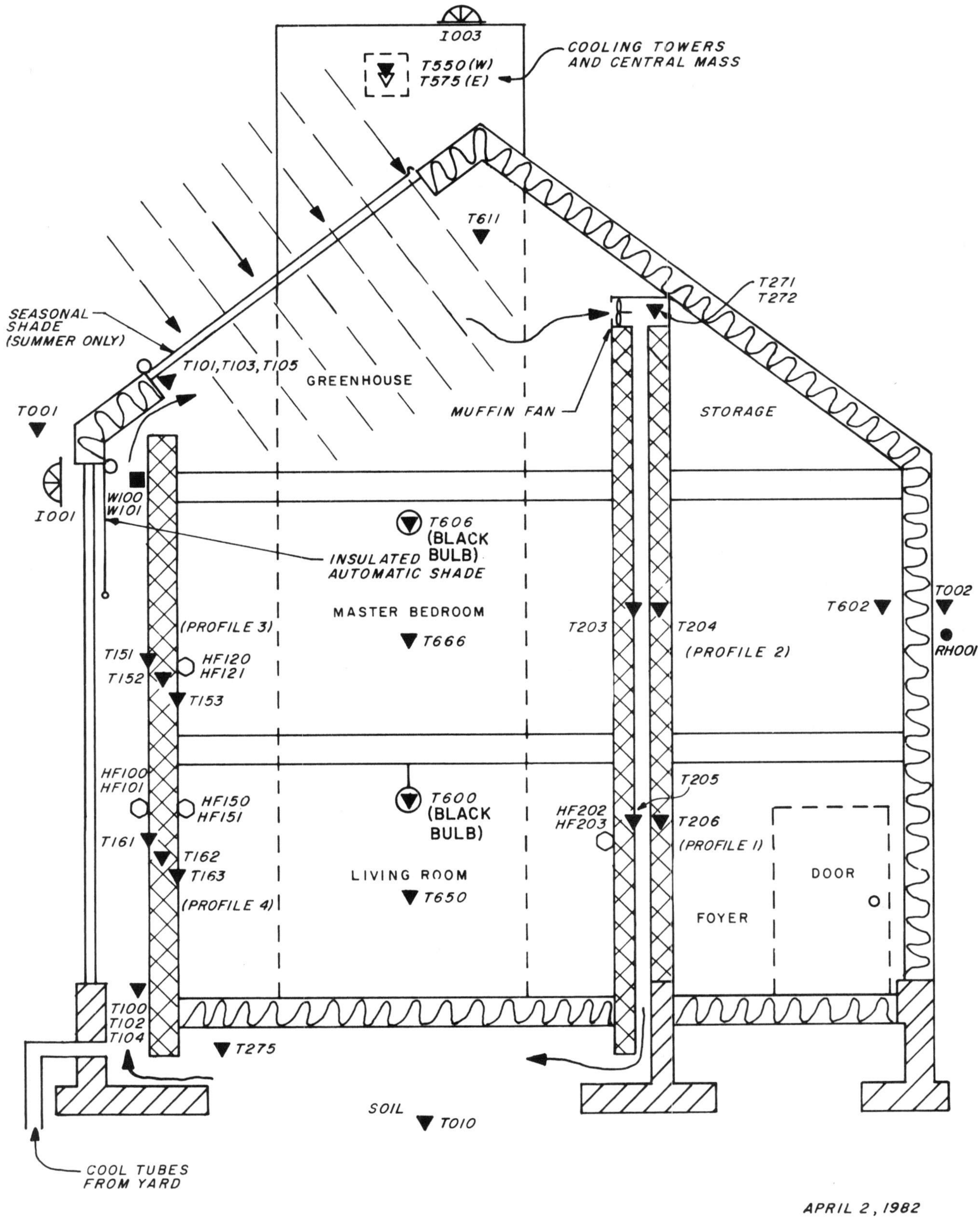
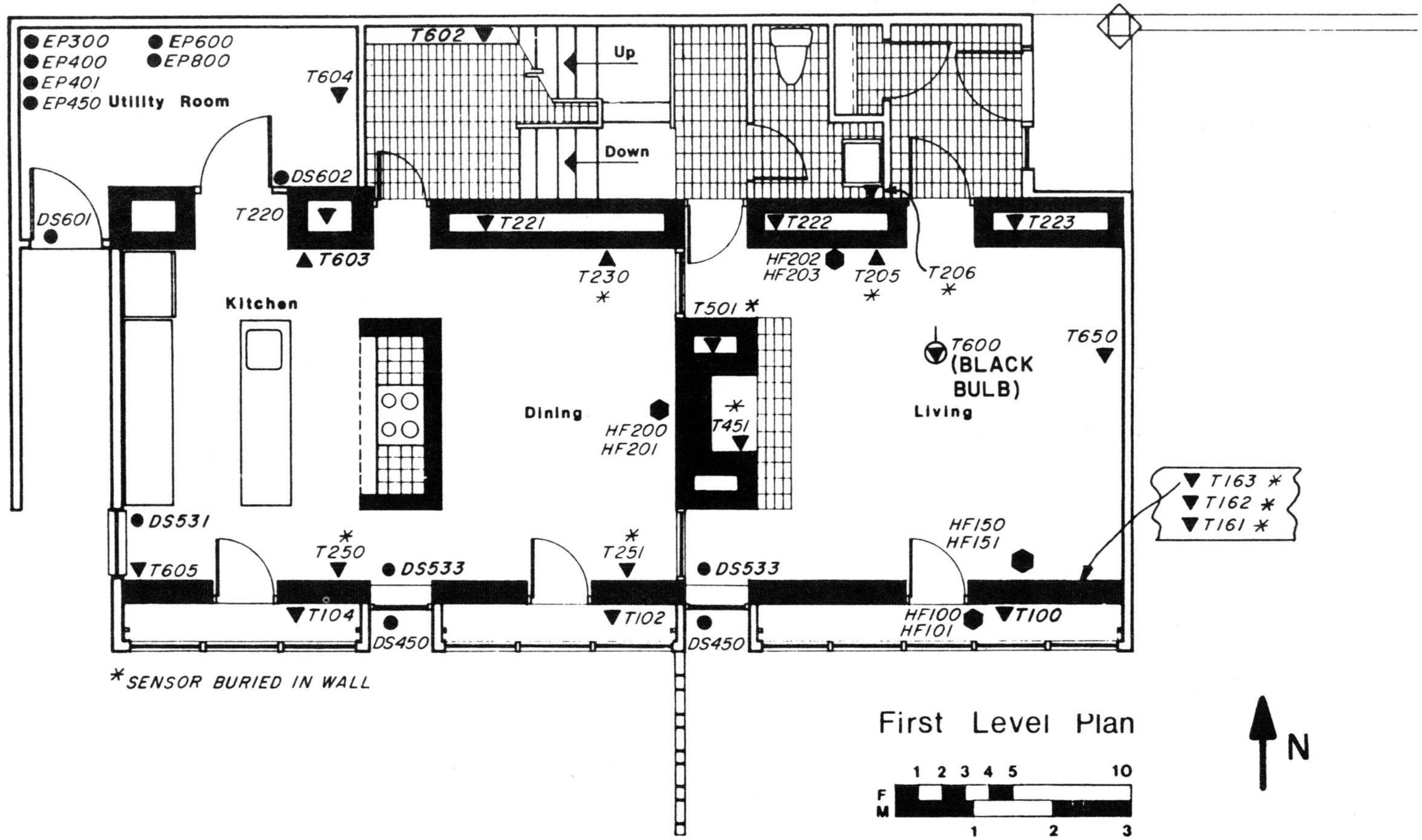
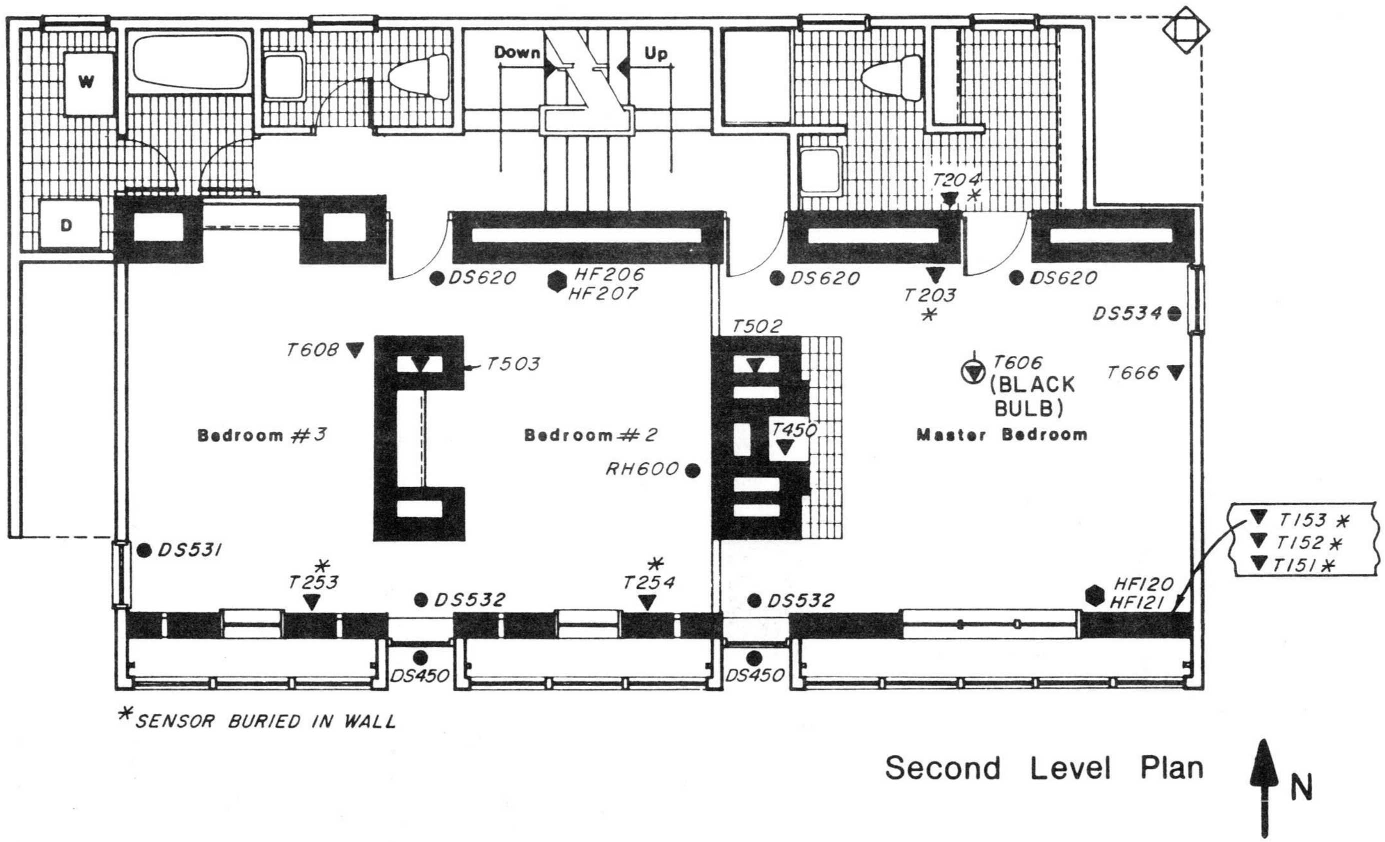



Figure A-2. Roberts Home Passive Solar Energy Schematic, Cross Section



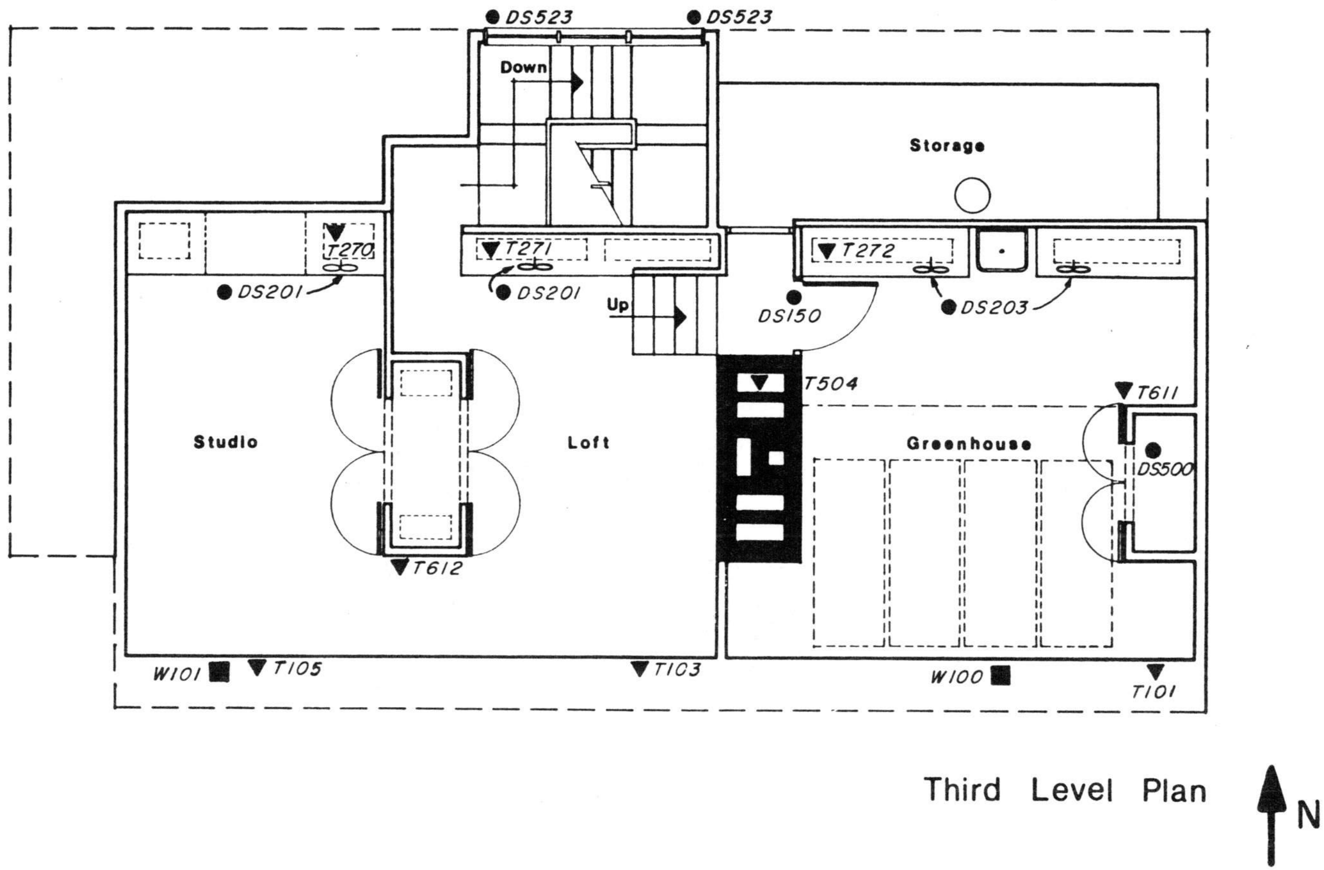

April 2, 1982

Figure A-3. Roberts Home Passive Solar Energy System Schematic, First Level Plan




2/11/82

Figure A-4. Roberts Home Passive Solar Energy System Schematic, Second Level Plan




April 2, 1982

Figure A-5. Roberts Home Passive Solar Energy System Schematic, Third Level Plan

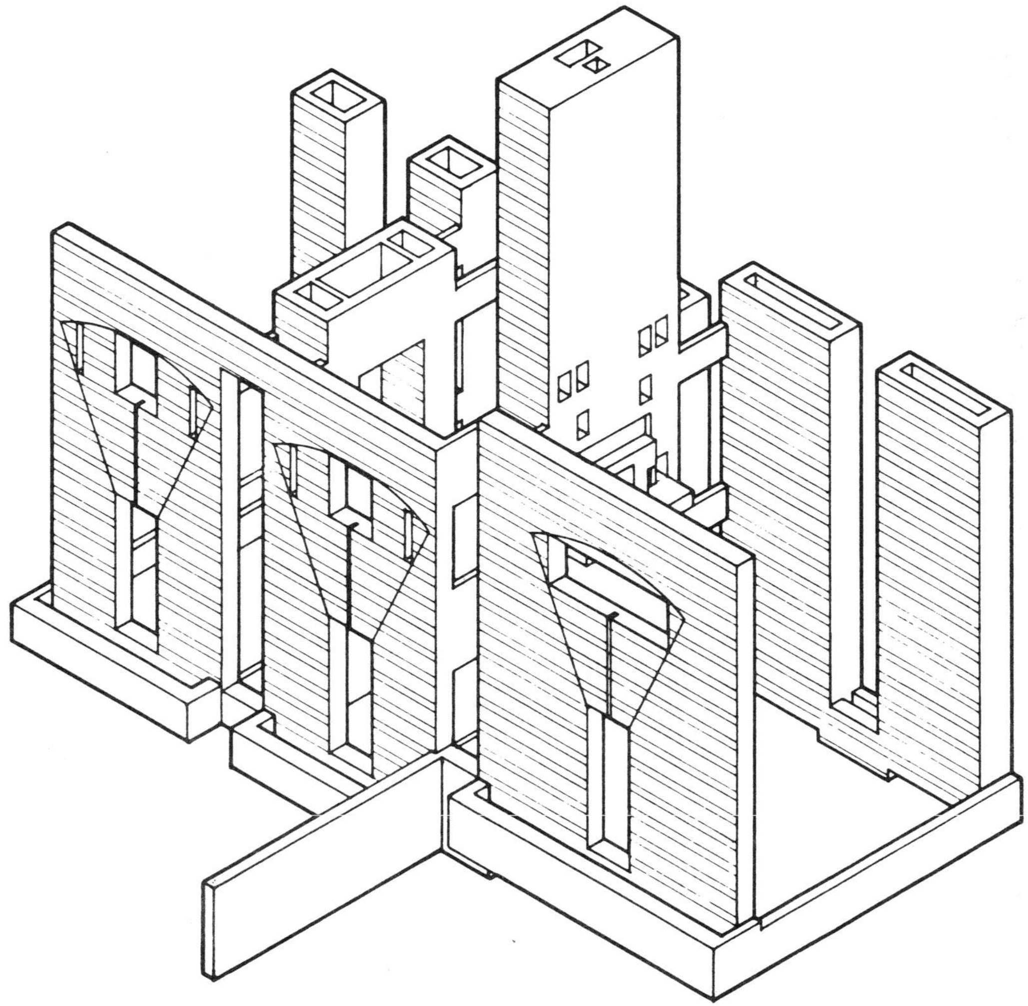


Figure A-6. Roberts Home Passive Solar Energy System Schematic, Mass Walls Configuration

## APPENDIX A-2

## SITE HISTORY, PROBLEMS

| Date | Event, Anomaly |
|---|---|
| 1/19/82 | Instrumentation and SDAS checkout. |
| 2/12/82 | Data collection begins. |
| 5/6/82 - 5/17/82 | SDAS down and data bridged. |
| 7/22/82 - 7/31/82 | SDAS down and data bridged. |

# APPENDIX B

# PERFORMANCE FACTORS AND SOLAR TERMS

# APPENDIX B

## PERFORMANCE FACTORS AND SOLAR TERMS

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

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

## SECTION 1

## GENERAL ACRONYMS

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

SECTION 2

## PERFORMANCE FACTOR DEFINITIONS AND ACRONYMS

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

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

* Primary Performance Factors

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

* Primary Performance Factor

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

* Primary Performance Factors

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

* Primary Performance Factors

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

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

* Primary Performance Factors

| ACRONYM | NAME | DEFINITION |
|---|---|---|
| HWOPE | HWS Operating Energy | Amount of energy required to support the HWS operation which is not intended to be applied directly to the HWS load. |
| HWOPE1 | Solar-Unique HWS Operating Energy | "Operating energy" necessary to the functioning of the solar energy portions of the HWS. |
| HWSE | Solar Energy to HWS | Amount of solar energy delivered to the HWS. |
| HWSE1 | Solar Energy to Preheat Tank | The amount of solar energy input to a preheat tank. |
| * HWSFR | HWS Solar Fraction | Percentage of the HWS load which is supported by solar energy. |
| * HWSVE | HWS Electrical Energy Savings | Difference in the electrical energy required to support an assumed similar conventional HWS and the actual electrical energy required to support the demonstration HWS, for identical HWS loads. |
| * HWSVF | HWS Fossil Energy Savings | Difference in the fossil energy required to support an assumed similar conventional HWS and the actual fossil energy required to support the demonstration HWS, for identical loads. |
| LINLOS | Recirculation Loop Losses | Thermal energy losses due to recirculation of hot water in a large building loop. |
| OUTVC | Cooling Produced | Space cooling provided by the air conditioner; energy removed from the conditioned space. |
| PARA | Rankine Parasitic Power | Amount of auxiliary electrical energy supplied per unit time to the refrigerant pump and the Rankine subsystem controls. |

* Primary Performance Factors

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

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

* Primary Performance Factors

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

* Primary Performance Factors

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

* Primary Performance Factors

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

* Primary Performance Factors

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

* Primary Performance Factor

## PERFORMANCE FACTOR DEFINITIONS AND ACRONYMS FOR ROBERTS HOME (PASSIVE SYSTEM)

| ACRONYM | NAME | DEFINITION |
|---|---|---|
| ACH | Air Changes Per Hour | Infiltration rate given in total house volume air changes per hour. |
| BHSFR | Building Solar Fraction | Percentage of "building heat load" provided by "passive solar used." |
| CLEF_SS | Sunspace Collector Efficiency | The percentage of available solar energy which is delivered to the space heating load by the sunspace; i.e., the net gains divided by the total solar energy available to the sunspace |
| CLEF_TW | Trombe Wall Collector Efficiency | The percentage of available solar energy which is delivered to the space heating load by the Trombe wall; i.e., the net gains divided by the total solar energy available to the Trombe wall. |
| COPE_FAN | Oscillating Fans Operating Energy | Electrical energy required to operate the oscillating fans. |
| CSEP | Passive Cooling | The portion of the cooling load which is satisfied by the cooling subsystem. |
| CSFR | Passive Cooling Solar Fraction | The percentage of the equipment cooling load which is provided by the passive cooling subsystem. |
| CSOPE_CUR | Insulating Curtain Operating Energy | The electrical energy required to operate the Trombe wall insulating curtain. |

| ACRONYM | NAME | DEFINITION |
|---|---|---|
| CSOPE_FAN | Air-Core Fans Operating Energy | The electrical energy required to operate the fans which draw air from the space between the Trombe wall and the glazing to heat the rear air-core mass wall. |
| CTSVE | Cooling Energy Savings | The difference in the estimated electrical energy required to support an assumed conventional cooling load and the actual electrical energy used. |
| ECL | Equipment Cooling Load | The amount of cooling which a conventional cooling system would be required to produce to satisfy the cooling load. |
| EHSFR | Solar Fraction Equipment Heating Load | Percentage of "equipment heating load" supplied by "passive solar used." |
| HFIRE | Auxiliary Energy Fireplaces | Energy contributed to space heating by fireplaces. |
| HI | Infiltration Losses | Heat convected through cracks, doors, and windows as air movement. |
| HLUA | Conduction Losses (UA$\Delta$T) | Heat conducted out through the building walls. The overall heat transfer coefficient is U. The area of walls and ceiling is A. The difference in temperature between the inside and outside the building is $\Delta$T. |
| HOTHER | Auxiliary Energy Internal Gains | Energy provided for space heating by active solar elements, lights, people, appliances, etc. inside the building. |

| ACRONYM | NAME | DEFINITION |
|---|---|---|
| HSEP | Passive Solar Used | This performance factor can only be inferred from other energy transfers by the energy balance method. It is the energy lost through the building insulation, "UAΔT," and the "infiltration losses," but not including "auxiliary thermal used," nor "auxiliary energy internal gains." The measurements of these factors is uncertain, thus "passive energy used" is the least accurate of the factors. |
| ICH | Indoor Comfort Hours | The number of hours during the day when the inside temperatures and relative humidity are within the ASHRAE defined comfort limits (temperatures between 72°F and 77°F and relative humidity between 20% and 60%. |
| MI_TIME | Time Movable Insulation is In Place | The number of hours per day when the insulating curtain on the Trombe wall is closed. |
| MSTECH | Building Storage | The energy stored in the mass of the building and its contents not including the parts of the building added mainly for passive storage. |
| NET_GAIN | Collection Subsystem Net Gain | The total net energy gains of all elements of the collection subsystem; i.e., the sum of the short-wave solar gains less the long-wave heat losses. |
| NET_GAIN_SS | Sunspace Net Gains | The net energy gains of the sunspace collection subsystem; i.e., the sum of the short-wave solar gains less the long-wave heat losses. |

| ACRONYM | NAME | DEFINITION |
|---|---|---|
| NET_GAIN_TW | Trombe Wall Net Gains | The net energy gains of the Trombe wall collection subsystem; i.e., the sum of the short-wave solar gains less the long-wave heat losses. |
| NET_RAD_GAIN | Radiant Cooling Net Load | Net energy gain from solar radiation absorbed by the building. |
| OCH | Outdoor Comfort Hours | The number of hours during the day when outside temperatures and relative humidity are within the ASHRAE defined comfort limits (temperatures between 72°F and 77°F and relative humidity between 20% and 60%). |
| PSTECH | Passive Storage | The energy stored in the storage mass of the passive system. |
| RHIN | Indoor Relative Humidity | Average relative humidity inside the building during the reporting period. |
| SE_SS | Incident Solar Energy on Sunspace | Accumulated total incident solar energy per unit area measured in the plane of the sunspace glazing. |
| SEA_SS | Incident Solar Energy on the Sunspace | Amount of solar energy incident on the sunspace glazing. |
| SEA_TW | Incident Solar Energy on the Trombe Wall | Amount of solar energy incident on the Trombe wall glazing. |
| SECA_SS | Solar Energy Collected by the Sunspace | The amount of solar energy collected by the sunspace. |
| SECA_TW | Solar Energy Collected by the Trombe Wall | The amount of solar energy collected by the Trombe wall. |

| ACRONYM | NAME | DEFINITION |
|---|---|---|
| SEH | Horizontal Incident Solar Energy | Accumulated total incident solar energy per unit area measured on the horizontal plane at the site. |
| SEOP_SS_TRANS | Sunspace Transmittance | The average transmittance of the sunspace glazing. |
| SEOP_TRANS | Collector Transmittance | The average transmittance of the collector glazing. |
| SEOP_TW | Trombe Wall Operational Incident Solar Energy | Solar energy incident on the Trombe wall when the insulating curtain is open. |
| SEOP_TW_TRANS | Trombe Wall Transmittance | The average transmittance of the Trombe wall glazing. |
| SG_HL | South Glass Heat Loss | Total heat loss through all of the south glazing. |
| SS_TA_MIN | Minimum Sunspace Temperature | The minimum daily air temperature in the sunspace. |
| SS_TA | Sunspace Temperature | Average temperature of the air in the sunspace. |
| SS_TA_MAX | Maximum Sunspace Temperature | The maximum daily air temperature in the sunspace. |
| SS_TDA | Sunspace Daytime Temperature | Average temperature of the air in the sunspace during the period three hours before noon to three hours after noon. |
| TB_MAX | Maximum Building Temperature | The maximum temperature of the air in the building. |
| TB_MIN | Minimum Building Temperature | The minimum temperature of the air in the building. |

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## SECTION 3

## SOLAR TERMINOLOGY

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

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

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

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

**Instantaneous Efficiency Curve** — A plot of solar collector efficiency against operating point, $\frac{Ti - Ta}{I}$, (see Operating Point).

**Load** — That to which energy is supplied, such as space heating load or cooling load. The system load is the total solar and auxiliary energy required to satisfy the heating or cooling requirements.

**Manifold** — The piping that distributes the transport fluid to and from the individual panels of a collector array.

**Microclimate** — Highly localized weather features which may differ from long-term regional values due to the interaction of the local earth's surface with the atmosphere.

**Nocturnal Radiation** — The loss of thermal energy by the solar collector to the night sky.

**Operating Energy** — The amount of energy (usually electrical energy) required to operate the solar and auxiliary equipments and to transport the thermal energy to the point of use, and which is not intended to directly affect the thermal state of the system.

**Operating Point** — A solar energy system has a dynamic operating range due to changes in level of insolation (I), fluid input temperature (Ti), and outside ambient temperature (Ta). The operating point is defined as:

$$\frac{Ti - Ta}{I}\left(\frac{^{o}F \times hr \times ft^2}{BTU}\right)$$

**Operational Collector Efficiency** — Ratio of collected solar energy to incident solar energy only during the time the collector fluid is being circulated with the intention of delivering solar-source energy to the system.

**Outgassing** — The emission of gas by materials and components, usually during exposure to elevated temperature, or reduced pressure.

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

| | |
|---|---|
| Stratification | A phenomenon that causes a distinct thermal gradient in a heat transfer fluid, in contrast to a thermally homogeneous fluid which results in the layering of the heat transfer fluid, with each layer at a different temperature. In solar energy systems, stratification can occur in liquid storage tanks or rock beds, and may even occur in pipes and ducts. The temperature gradient or layering may occur in a horizontal, vertical, or radial direction. |
| System Performance Factor | Ratio of system load to the total equivalent fossil energy expended or required to support the system load. |
| Ton of Refrigeration | The heat equivalent to the melting of one ton (2,000 pounds) of ice at 32°F in 24 hours. A ton of refrigeration will absorb 12,000 BTU/hr, or 288,000 BTU/day. |
| Tracking Collector | A solar collector that moves to point in the direction of the sun. |
| Zone | A portion of a conditioned space that is controlled to meet heating or cooling requirements separately from the other space or other zones. |

# APPENDIX C

# DATA ACCURACY AND PERFORMANCE EQUATIONS

# APPENDIX C

# DATA ACCURACY AND PERFORMANCE EQUATIONS

# ROBERTS HOME

## INTRODUCTION

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

## DATA ACCURACY ESTIMATES

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

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

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

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

Table C-1. SENSOR ACCURACY

THE NATIONAL SOLAR DATA NETWORK

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

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

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

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

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

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

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

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

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

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

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

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

## PERFORMANCE FACTORS

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

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

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

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

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

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

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

For a liquid system, $\Delta H$ is generally given by

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

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

For an air system, $\Delta H$ is generally given by

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

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

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

For electrical power, a general example is

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

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

Letter Designations

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

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

## EQUATIONS USED TO GENERATE MONTHLY PERFORMANCE VALUES

### ENVIRONMENTAL FACTORS

AMBIENT TEMPERATURE (°F)

TA = (T001 + T002)/2

TDA = TA ± 3 HOURS FROM SOLAR NOON

HEATING DEGREE-DAYS

HDD = 65 - TA

if (TA_MAX + TA_MIN)/2 <65

COOLING DEGREE-DAYS

CDD = TA - 65

if (TA_MAX + TA_MIN)/2 >65

INCIDENT SOLAR ENERGY IN THE PLANE OF THE TROMBE WALL ($BTU/FT^2$)

SE = I001

HORIZONTAL INCIDENT SOLAR ENERGY

SEH = I003

INCIDENT SOLAR ENERGY IN THE PLANE OF THE SUNSPACE ($BTU/FT^2$)

SE_SS = I003 x RBAR

RBAR = CORRECTION FOR TILT

TOTAL INCIDENT SOLAR ENERGY ON TROMBE WALL (BTU)

SEA_TW = SE x CLAREA_TW

CLAREA_TW = 663

TOTAL INCIDENT SOLAR ENERGY ON SUNSPACE (BTU)

SEA_SS = SE_SS x CLAREA_SS

CLAREA_SS = 99

TOTAL INCIDENT SOLAR ENERGY (BTU)

SEA = SEA_TW + SEA_SS

OUTDOOR RELATIVE HUMIDITY (%)

RELH = RH001

## BUILDING PERFORMANCE FACTORS

BUILDING HEAT LOAD (BTU)

BL = HLUA + HI

HLUA = UAΔT WALLS + UAΔT FLOOR + UAΔT ROOF +

UAΔT GLASS + UAΔT DOORS

HI = VOLUME x 0.075 x (TB - TA) x ACH

VOLUME = 13904

ACH = 0.5

EQUIPMENT HEAT LOAD (BTU)

EHL = BL - HOTHER

AUXILIARY HEATING (BTU)

HAT = HAE + HFIRE

HAE = EP400 + EP401 x EPCONSTANT

AUXILIARY HEAT FROM FIREPLACE (BTU)

HFIRE = HFIRE1 + HFIRE2

HFIRE1 = 5000 BTU/HR IF T451 >T501 + 4

HFIRE2 = 3000 BTU/HR IF T450 >T502 + 4

INTERNAL GAINS (BTU)

HOTHER = EP600 - (EP400 + EP401) - (EP300 x 0.2)

PASSIVE SOLAR ENERGY USED (BTU)

HSEP = EHL - HAT

BUILDING SOLAR FRACTION (%)

BHSFR = (HSEP/BL) x 100

EQUIPMENT SOLAR FRACTION (%)

EHSFR = (HSEP/EHL) x 100

BUILDING TEMPERATURE (°F)

TB = (T603 + T605 + T650 + T608 + T666 + T612)/6

TB_MAX = MAXIMUM DAILY VALUE TB

TB_MIN = MINIMUM DAILY VALUE TB

BUILDING RELATIVE HUMIDITY (%)

RHIN = RH600

SUNSPACE TEMPERATURES (°F)

SS_TA = T611

SS_TDA = T611 ± 3 HOURS FROM NOON

SS_TA_MAX = MAX DAILY VALUE T611

SS_TA_MIN = MINIMUM DAILY VALUE T611

BUILDING COOLING LOAD (BTU)

CL = NET_RAD_GAIN + HOTHER + SYSOPE + NET_GAIN

NET_RAD_GAIN = BUILDING SURFACE AREA x QRAD

BUILDING SURFACE AREA = 498

QRAD = (SEH x 0.83) - 28.9

EQUIPMENT COOLING LOAD (BTU)

ECL = CL - HLUA

AUXILIARY COOLING (BTU)

CAT = EP450 x EPCONST x COP

COP = 2.5 (average)

PASSIVE COOLING (BTU)

CSEP = ECL - CAT

PASSIVE COOLING FRACTION (%)

CSFR = (CSEP/ECL) x 100

ASHRAE COMFORT INDEX (HOURS)

OCH = 1 IF TA >72 AND <77 AND RELH >20 AND <60

ICH = 1 IF TB >72 AND <77 AND RHIN >20 AND <60

OPERATING ENERGY (BTU)

SYSOPE = CSOPE_FAN + CSOPE_CUR + COPE_FAN

CSOPE_FAN = DS201, DS203 x FAN CONSTANT

CSOPE_CUR = DS160 x MOTOR CONSTANT

COPE_FAN = 12 HR/DAY x 75 WATTS (estimated by owner)

## COLLECTION SUBSYSTEM FACTORS

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

SEOP = SEA x DS160

SEOP_TW = SEA_TW x DS160

MOVABLE INSULATION TIME IN PLACE (HOURS/DAY)

MI_TIME = 1 WHEN DS160 = 0

COLLECTED SOLAR ENERGY (BTU)

SECA = HSEP - STECH

SECA_SS = SEA_SS x 0.65 WINTER AND 0.25 SUMMER (after 4/18/83)

SECA_TW = SECA - SECA_SS

NET GAINS (BTU)

NET_GAIN = NET_GAIN_TW + NET_GAIN_SS

NET_GAIN_TW = SECA_TW - UAΔT_TW

NET_GAIN_SS = SECA_SS - UAΔT_SS

SS_HL = UAΔT_SS _ UAΔT_TW

OPERATING COLLECTOR TRANSMITTANCE (%)

SEOP_TRANS = SECA/SEA

SEOP_TW_TRANS = SECA_TW/SEA_TW

SEOP_SS_TRANS = SECA_SS/SEA_SS

OVERALL COLLECTOR EFFICIENCY (%)

CLEF = NET_GAIN/SEA

CLEF_TW = NET_GAIN_TW/SEA_TW

CLEF_SS = NET_GAIN_SS/SEA_SS

STORAGE SUBSYSTEM

STORAGE TEMPERATURE (°F)

TST = (T254 + T253 + T251 + T250 + T162 + T151 + T502 + T503 + T206 + T205 + T204 + T203 + T230)/13

CHANGE IN STORED ENERGY (BTU)

MSTECH = ΔTB x BLDG.MASS x BLDG.CP

BLDG.MASS = 8500

BLDG.CP = 0.22

PSTECH = ΔTST x STOMASS x STOCP

STOMASS = 266880

STOCP = 0.22

STECH = MSTECH + PSTECH

ENERGY TO STORAGE (BTU)

STEI = PSTECH

ENERGY FROM STORAGE (BTU)

STEO = -PSTECH

ENERGY SAVINGS (KWH)

$$HSVE = HSEP \times 292.8 \times 10^{-6} \text{ KWH/BTU}$$

$$CSVE = CSEP \times 292.8 \times 10^{-6} \text{ KWH/BTU/2.5}$$

$$TSVE = HSEP - SYSOPE$$

$$CTSVE = CSEP - SYSOPE$$

APPENDIX C

# REFERENCES


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

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

# APPENDIX D

# LONG-TERM WEATHER DATA

# APPENDIX D

## LONG-TERM WEATHER DATA

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

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

# ROBERTS HOME LONG-TERM WEATHER DATA

COLLECTOR TILT: 48 DEGREES
LATITUDE: 38.8 DEGREES

LOCATION: RESTON, VIRGINIA
COLLECTOR AZIMUTH: -8 DEGREES

| MONTH | HOBAR | HBAR | KBAR | RBAR | SBAR | HDD | CDD | TBAR |
|---|---|---|---|---|---|---|---|---|
| JAN | 1393. | 571. | 0.41012 | 1.516 | 867. | 1020 | 0 | 32. |
| FEB | 1853. | 815. | 0.43974 | 1.180 | 962. | 874 | 0 | 34. |
| MAR | 2442. | 1125. | 0.46049 | 0.844 | 949. | 719 | 0 | 42. |
| APR | 3048. | 1460. | 0.47898 | 0.582 | 850. | 367 | 0 | 53. |
| MAY | 3470. | 1718. | 0.49520 | 0.439 | 755. | 131 | 57 | 63. |
| JUN | 3639. | 1902. | 0.52285 | 0.383 | 729. | 5 | 188 | 71. |
| JUL | 3548. | 1818. | 0.51225 | 0.407 | 740. | 0 | 319 | 75. |
| AUG | 3206. | 1619. | 0.50489 | 0.512 | 829. | 0 | 267 | 74. |
| SEP | 2657. | 1342. | 0.50508 | 0.737 | 989. | 43 | 100 | 67. |
| OCT | 2023. | 1003. | 0.49577 | 1.095 | 1098. | 291 | 9 | 56. |
| NOV | 1499. | 653. | 0.43522 | 1.447 | 944. | 609 | 0 | 45. |
| DEC | 1267. | 483. | 0.38116 | 1.583 | 765. | 961 | 0 | 34. |

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.
HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.
KBAR ==> RATIO OF HBAR TO HOBAR.
RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).
SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.
HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.
CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.
TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

# APPENDIX E

# ENERGY CONVERSION FACTORS

# APPENDIX E

## ENERGY CONVERSION FACTORS

| Fuel Type | Energy Content | Fuel Source Conversion Factor |
|---|---|---|
| Coal | 8,600 BTU/pound<br>$17.2 \times 10^6$ BTU/ton | $0.05814 \times 10^{-6}$ tons/BTU |
| Electricity | 3,413 BTU/kilowatt-hour | $292.8 \times 10^{-6}$ kwh/BTU |
| Kerosene | 135,000 BTU/gallon | $7.41 \times 10^{-6}$ gallons/BTU |
| Natural gas | 1,021 BTU/cubic foot | $979.4 \times 10^{-6}$ cubic feet/BTU |
| Oil, distillate fuel[1] | 138,690 BTU/gallon | $7.21 \times 10^{-6}$ gallons/BTU |
| Oil, residual fuel[2] | 149,690 BTU/gallon | $6.68 \times 10^{-6}$ gallons/BTU |
| Propane | 91,500 BTU/gallon | $10.93 \times 10^{-6}$ gallons/BTU |
| Wood[3] | 20-25 million BTU/cord | |

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

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

[3] Energy content varies widely depending on the type of wood and the moisture content of the wood



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