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PERFORMANCE OF A DRAIN-BACK SOLAR HEATING AND HOT WATER
SYSTEM WITH AUXILIARY HEAT PUMP

Final Report

By
S. Karaki

March 1984

Work Performed Under Contract No. AC03-81CS30569

Colorado State University
Solar Energy Applications Laboratory
Fort Collins, Colorado

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SOLAR HEATING AND HOT WATER SYSTEM
WITH AUXILIARY HEAT PUMP

FINAL REPORT

PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
CONSERVATION AND SOLAR APPLICATIONS

Prepared by

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March 1984

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EXECUTIVE SUMMARY

INTRODUCTION

The solar system that was planned for Solar House III during the summer and winter of 1982-83 consisted of 55 m² of BNL plastic collectors providing thermal energy for the XWF-3600 Arkla chiller during the summer and direct solar heating in a drain-back mode during the winter. Since the BNL collectors delaminated under stagnation conditions, the Chamberlain collectors were reinstalled during the Fall of 1982. Although the collectors have mild-steel absorber plates, if operated in a nitrogen environment, they could be utilized in a drain-back design. System modifications were accordingly made and data collection began on December 13, 1982. A schematic drawing of the system is shown in Figure 1.

Figure 1. System schematic of Solar House III for winter 1982-83.

Collector Array

The collector array was divided into two rows, each as a 1-high array. The top row was manifolded in a reverse-return configuration, and the bottom row was manifolded to minimize piping. The piping arrangements for both arrays are shown in Figure 2.

Figure 2. Manifolding arrangements for top and bottom arrays on Solar House III.

Although the plan was to pressurize the system with nitrogen, leakage in several absorber plates was so high that pressurization became impractical, and the collectors operated through the winter season as a vented system.

RESULTS

Collector Performance

Except for December, the lower collector array with the straight manifolding arrangement had lower efficiency than the upper array with the reverse-return piping. The difference was about 2 percentage

points. Unfortunately no definite conclusion can be drawn about the advantages of either manifold arrangement because the collectors in the arrays were not performing equally well. Considerable amounts of condensate accumulated on some cover plates because of leaks in the absorbers. Although quantitative measurements were not made, transmissivity and reflectivity were certain to have been affected.

System Performance

A summary of system performance measures is given in Table 1. Monthly average collector (total array) performance, and contributions

Table 1. Monthly Mean Daily Quantities of Performance Indicators.

LINE NO.	ITEM	UNITS	DEC	JAN	FEB	MAR	APR	SEASON
1	Days of Data		18	27	27	30	19	121
2	Total Insolation	(MJ/m ² ·day)	13.55	14.61	17.60	15.75	19.33	16.14
3	Insolation while Collecting	(MJ/m ² ·day)	10.40	11.83	13.22	11.28	13.55	12.06
4a	Thermal Energy Collected	(MJ/m ² ·day)	5.29	5.81	6.73	5.51	6.35	5.95
4b	Thermal Energy Collected	(MJ/day)	289.3	317.4	367.7	301.2	347.1	325.1
5	Collector Operating Efficiency	(4a÷3)	0.51	0.49	0.51	0.49	0.47	0.49
6	Collector Daily Efficiency	(4a÷2)	0.39	0.40	0.38	0.35	0.33	0.37
7	Total Heating Load	(MJ/day)	482.2	407.2	436.2	400.1	411.6	423.8
	a. Space Heating Load	(MJ/day)	470.4	343.9	335.1	307.9	317.4	347.7
	b. DHW Heating Load	(MJ/day)	11.8	63.3	101.1	92.2	94.2	76.1
8	Solar Energy Utilized	(MJ/day)	234.5	257.6	309.5	226.6	248.4	256.6
	a. Space Heating Supplied	(MJ/day)	234.5	240.2	257.4	182.7	201.3	222.8
	b. DHW Heating Supplied	(MJ/day)	0.0	17.4	52.1	43.9	47.1	33.8
9	Auxiliary Thermal Energy Utilized	(MJ/day)	247.7	149.7	126.7	173.5	163.2	167.2
	a. Auxiliary Space Heating	(MJ/day)	235.3	103.7	77.7	125.3	116.1	124.8
	i. Heat Pump	(MJ/day)	157.3	100.4	61.2	102.7	78.0	97.2
	ii. Electric Resistance	(MJ/day)	78.6	3.3	16.5	22.6	38.1	27.6
	b. Auxiliary DHW Heating	(MJ/day)	11.8	46.0	49.0	48.2	47.1	42.4
10	Solar Fraction for Total Heating	(8÷7)	0.49	0.63	0.71	0.57	0.60	0.61
	a. Solar Space Heating Fraction	(8a÷7a)	0.50	0.70	0.77	0.59	0.63	0.64
	b. Solar DHW Heating Fraction	(8b÷7b)	0.0	0.27	0.52	0.48	0.50	0.44
11	Solar System Efficiency	8÷(2×Ac)	0.32	0.32	0.32	0.26	0.24	0.29

* Values in this table are based on gross collector area of 54.65 m².

of solar energy towards space and water heating loads are shown in Figures 3, 4, and 5. Average daily collection efficiency for the season was 37 percent, which is lower than the 48 percent recorded in previous years. However, it should be noted that the 1982-83 winter season was mild, and warm months lead to lower collector efficiency because the water temperature in storage can be high.

The contribution of solar energy to DHW heating is disturbingly low. A forced DHW load profile with 75 liters per dumping event may contribute to the poor performance.

Figure 3. Collector performance 1982-83 winter heating season Solar House III.

Figure 4. Monthly average daily space heating loads and proportions supplied by solar, heat pump and electric resistance heating.

Figure 5. Monthly average daily DHW load, solar and electric resistance contributions.

CONCLUSION

1. The Chamberlain collectors have deteriorated in performance compared to previous seasons. Where daily efficiency of 41 percent were attained in 1978-79 and 1979-80, efficiency was 37 percent. System efficiency of 29 percent compares to 30 percent in prior years.

2. Solar contribution to DHW heating is low, and is probably the result of the artificially imposed load profile and the low recovery rate of the double-wall heat exchanger.

3. System efficiency can be improved by reducing thermal losses from storage.

PERFORMANCE OF A DRAIN-BACK
SOLAR HEATING AND HOT WATER SYSTEM
WITH AUXILIARY HEAT PUMP

1.0 INTRODUCTION

1.1 Objective of the Project

The principal objective of the project was to test and evaluate the BNL collectors in a space heating system. When the BNL collectors delaminated under stagnation conditions, they were replaced with the Chamberlain collectors which were previously used on Solar House III, and tests were continued to evaluate performance of a drain-back system.

1.2 Description of the Environment

1.2.1 Location of the Project

Fort Collins, Colorado is located 96.6 km north of Denver, and the system being evaluated was in Solar House III which is located in the Colorado State University Solar Village. The project site is 6.4 km west of the City of Fort Collins at approximately 40.6° N latitude and 105.1° W longitude and the elevation of the site is 1585 m above sea level. The solar village consists of a group of 5 buildings with experimental solar heating and cooling systems, including active, passive, and hybrid systems. Situated on a southward sloping terrain, the solar systems are unaffected by adjacent buildings. The terrain to the east and south generally is open and flat, but a high range of mountains is located immediately to the west. While the mountains do not shade the solar village during the summer until well after the solar systems have stopped collecting, on December 21, the shadow of the foothill range covers the village by 3:30 p.m.

1.2.2 Climate

The climate in winter is characterized by moderate temperatures, light precipitation and light winds, interrupted occasionally by strong north-westerly winds associated with the passage of a specific combination of weather fronts. The monthly average daily temperatures, from September through April during the heating season, vary from about 17 C to -2 C in January and about 10 C in April. The temperatures are moderated sporadically by warm chinook winds from the south.

The average annual precipitation in Fort Collins is about 370 mm, most of which falls during the spring which marks the growing season in Colorado (March, April and May). Afternoon thunderstorms occur frequently during the summer months but they are usually accompanied by light rainfall amounts.

The normal total annual heating degree days is about 3600 C-days (18.3 C base). The monthly average daily radiation on a horizontal surface varies from about 17 MJ/(m² day) at the equinoxes to about 25 MJ/(m² day) in June and 7.5 MJ/(m² day) in December.

2.0 DESCRIPTION OF THE BUILDING AND SYSTEM

2.1 The Building

2.1.1 General Description

Solar House III is a residential-size building located in the Solar Village at the Foothills Research Campus of Colorado State University, Fort Collins, Colorado. The building size is appropriate for a three-bedroom house, although the rooms are used as offices for the staff of the Atmospheric Science Department. There are two levels in the building, each with about 128.5 m^2 (gross) floor area. The mechanical equipment for the solar system, other than the collectors, is located in the basement. A view of the south side of the building is seen in the photograph of Figure 2-1.

Figure 2-1. CSU Solar House III.

2.1.2 Plans, Elevations and Cross-Sections

The ground level and basement floor plans are shown in Figures 2-2 and 2-3, and elevation views as well as a cross-section of the building are shown in Figures 2-4 through 2-6. There is an attached room to the north connected to the building by an entrance way at ground level. The room, which would be an unheated garage to a residence, serves as graduate student offices and is partially heated by the solar system.

The main entrance to the building is at the first floor (ground) level and faces east, although entrance can be gained from the south door at basement level. The basement door opens directly to the mechanical equipment room.

The collectors are placed on the sheathing of the roof and face due south. As seen in Figure 2-6, there is a second, weather-proof, roof underlying the collector mounting surface, which is a special feature of this experimental building to permit periodic replacement of collectors.

Figure 2-2. First floor plan of Solar House III.

Figure 2-3. Basement floor plan of Solar House III.

Figure 2-4. East and south elevations of Solar House III.

Figure 2-5. North and west elevations of Solar House III.

Figure 2-6. Cross section of Solar House III.

There is an overhang of 1.83 m at the eave, and the roof is supported by vertical walls which serve both as structural members and shading for the windows on the south wall.

2.1.3 Building Materials and Heating Load

The building walls are constructed of 50x100 mm (2x4-in.) studs on 406 mm (16-in.) centers. The sheathing on the exterior is 12-mm plywood with a 10-mm thick plywood siding over it. The interior surface is 16-mm gypsum board and the space between studs is filled with glass fiber batt insulation. Ceiling joists are 50x150 mm (2x6-in.) beams on 610 mm centers, and covered with 165 mm of batt insulation.

The exposed wall area of the building totals about 110m^2 and the underground wall area is about 73m^2 . There are 28.25m^2 of double-glazed windows in wood frame with 80 percent glass area, and about 3.9m^2 of door area, half of which is a solid core door and the other door has 0.56m^2 of single pane glass. The calculated heat transmittance rate of the building is about 420 W/C, including an estimate of one air change per hour of infiltrating air.

2.2 The Solar System

The solar system consists of 54.5m^2 of single-glazed, selective surface Chamberlain collectors in a drain-back configuration with 4500 liters of water storage. An air-to-air heat pump provides auxiliary heating. A schematic drawing of the system is shown in Figure 2-7.

Figure 2-7. System schematic of Solar House III for winter 1982-83.

2.2.1 Solar Collectors

A cutaway view of the Chamberlain collector is shown in Figure 2-8. Each collector module is 1.95 m^2 gross area with 1.80 m^2 aperture area, and covered with a single glazing of low-iron, tempered glass. The absorber surface has a selective surface coating of black chrome on nickel, with a steel substrate. Fluid flows between plates that are spot welded in a patterned arrangement that gives an appearance of a dimpled surface. The backside of the absorber is insulated with rigid foam insulation and the collector is in a galvanized steel frame.

The collectors were placed on the roof of Solar House III in two rows, the top row being independent of the lower one. As an experimental variation, the top row was manifolded in a reverse return

Figure 2-8. Cutaway view of the Chamberlain collector.

arrangement and the lower array was connected in such a way as to minimize piping. The arrangements are shown in Figure 2-9.

2.2.2 Thermal Storage

Thermal energy is stored as sensible heat in water within a 4500-liter steel tank. The cylindrical horizontal steel tank is 1.353 m diameter (I.D.) and 2.819 m long and is supported by two saddles. Polyurethane foam was applied to the tank exterior to an average thickness of 100 mm.

2.2.3 Water-to-Air Heat Exchanger

The central duct coil for heat exchange from solar-heated water to room air is a 14-kW double-row unit made by Arkla. Air flow through the coil is controlled by the blower of the heat pump.

2.2.4 Heat Pump

A 3-ton split system, air-to-air, Trane heat pump is installed with the condenser in parallel with the solar coil. If the heat pump cannot supply the required heating, 15 kW resistance heating can adequately heat the rooms.

2.2.5 DHW Preheating

A double-walled heat exchanger and a single tank of 300-liter capacity serves DHW heating needs. The lower heating element in the tank is deactivated for this installation.

Figure 2-9. Manifolding arrangements for top and bottom arrays on Solar House III.

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3.0 SYSTEM CONTROLS AND MODES OF OPERATION

3.1 Controller

3.1.1 Programmable Controller

System control is provided by a programmable microprocessor unit, developed by GTE Products Corporation, that enables BASIC programmer language to be used to set control logic. MECA II (Modular Electronic Control Assembly) can utilize multiple analog and digital signals and switch closures, as inputs, and provide load drivers to control output devices. There is a crystal-controlled clock to time events or to control time-of-day functions. With 4000 bytes of memory, complex decision processes can be examined before activating any device or component in the solar system. A photograph of the controller, voltage supply and signal conditioners are shown in Figure 3-1. The voltage supply is at the top, signal conditioners are at the left and the MECA controller is along the lower right side in the photograph.

Because MECA II is programmable, there is considerable flexibility for making experimental changes in controlling a solar system. Regardless of the complexity of a control strategy, however, the ultimate decision is to turn a device "on" or "off" based on the condition at one or more input sensors. In the Solar House III system the output or controlled devices are pumps, blowers, dampers and the heat pump. Input devices are temperature sensors.

Figure 3-1. System controller.

3.1.2 Mechanical Devices

All mechanical devices in the Solar House III system are on or off devices. Pumps and blower motors rotate at fixed speeds, and damper are either in the open or closed position.

3.1.3 Temperature Sensors

Four silicon diode temperature sensors provide primary information to the MECA controller. A sensor, T_C , is located on the backside of the absorber plate of one collector in the top array; another, T_{ST} , is at the top of storage; a third, T_{SB} , is at the bottom of storage; and the fourth, T_R , is indoors within the conditioned space. The collector

plate and storage bottom temperature difference ($T_C - T_{SB}$) is used to control fluid circulation through the collector loop. Temperature at the top of storage, T_{ST} , provides the input for making decisions related to solar or auxiliary energy usage, and T_R initiates delivery of heat to the rooms.

3.1.4 Temperature Settings for System Controls

Temperature differences and temperature settings for the controller for winter operation were as follows:

1. Start collector fluid circulation, $T_C - T_{SB} = 10$ C.
2. Stop collector fluid circulation, $T_C - T_{SB} = 2$ C.
3. Start space heating, $T_R = 20$ C.
4. Stop space heating, $T_R = 22$ C.
5. Auxiliary heat pump heating, $T_{ST} < 30$ C.
6. Electric resistance heating, second stage thermostat.

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4.0 DATA ACQUISITION SYSTEM

4.1 General Description

The data acquisition system (DAS) consists of: (1) instrumentation to sense temperatures, temperature differences, air and water flow rates, barometric pressure and relative humidity; (2) an analog-to-digital (A/D) converter and data logger; (3) an on-line microcomputer with peripheral cassette drive, typewriter and CRT, for real-time data reduction; (4) a magnetic tape recorder to store data in digital form; and (5) an uninterruptible power supply. The components of the DAS are depicted in Figure 4-1.

Figure 4-1. Block diagram of the data acquisition system.

Complete scans were made every 5 minutes throughout the day, every day through the season. Some gaps in the data sequence were unavoidable.

4.2 Instruments

The instruments used for measurement of temperatures, temperature differences, water and air flow rates, barometric pressure, relative humidity, solar flux and auxiliary energy quantities are listed in Table 4-1. Listed also in the table are instrument types, manufacturers and models, range of each instrument, accuracies, and comments which reflect the experience in Solar House III.

4.2.1 Solar Flux

Solar radiation measurements are made with Eppley PSP pyranometers placed on the roof of Solar House III. Total and diffuse radiation are measured on a horizontal plane and total radiation is also measured in a plane parallel to the collectors which are tilted at 45 degrees with respect to the horizontal. Both instantaneous and integrated values of solar radiation are included in the data set.

4.2.2 Temperature and Temperature Differences

Copper-constantan (Type T) thermocouples are used to measure temperatures of both air and water. Sheathed thermocouples are used to measure water temperatures. Reference junction compensation and linearization are provided by the data logging unit.

Temperature differences are measured with multiple-junction thermopiles, and electrical output is converted to temperature differences according to standard procedures. Five-junction thermopiles are used for water temperature differences. Temperature differences in air are measured with nine- or sixteen-junction thermopiles with each junction located in the center of equal area grids.

Table 4-1. Transducers and Specifications.

FUNCTION	INSTRUMENT TYPE	MANUFACTURER, DESCRIPTION	QUANTITY	INSTRUMENT/ DATA RANGE	(i) ACCURACY	COMMENTS
Temperature measurement (2)	Thermocouple Type T	Leeds and Northrup, 67 Omega, Thermo-Electric: 22 and 26 gage ThermoElectric, sheathed: Grounded (3) 2 Ungrounded (3) 2		-184 to +390°C -40 to +150°C	±0.4°C	Consider: Temperature gradients, heat transfer to and from the measuring junctions, thermoelectric homogeneity of wire, reference junction calibration, linearization errors, use of extension wire and connections, mechanical integrity, grounding, common mode voltage sources (including lightning).
Differential temperature measurement (2), (4)	Thermopile, Type T	Leeds and Northrup, 7 Omega 26 gage	7	-184 to 370°C ±100°C diff.	±(1 % R + 0.05°C)	
Water flow	Turbine Flowmeter	Cox, Series 21	3	0.19-1.9 µs	0.5 % F	Pressure drop at maximum flow, 5.5 psi.
Air flow	Vane-type Anemometer	Assembled by Nat'l. 1 Research Council of Canada	1	0.15-15.2 µs	not specified	
Solar flux measurement on 45° tilt	Pyranometer	Eppley precision pyranometer Model PSP	3	0 to 2800 w/m ² 0 to 1200 w/m ²	±(1.5 % R + 0.5 % F)	Both instantaneous and integrated values of pyranometer output are logged. A "double-glazed" pyranometer with axially symmetric black and white sensing surfaces is required to maintain accuracy when measuring global radiation on a tilt.
Electric power transducers	Current coil and hall effect transducer	F. W. Bell, Inc., PX-2202B Ohio Semitronics, PC5	6 5	±1 KW or ±2 KW 0 to 800 W	±(0.25 % R + 0.25 % F)	Models offered by Ohio Semitronics are available with offset, scale factor adjustments and in a greater range of capacities.
Integrators Pulse counters		AGM Electronics EA-4011-5 AGM Electronics EA-4050-2	12 4	Unipolar input/output range specified per individual module	±(0.25 % R + 0.25 % F)	Pick range carefully. Large accumulated errors due to effect avoiding by settling offsets slightly negative and rejecting negative values during data processing.
Barometric pressure	Variable capacitance diaphragm; vacuum reference	Rosemont 1332A Mercury Weathertronics	1 1	0 to 15 psia 0.73 to 0.83 atm 508-790 mmHg	±0.2 % R ±0.1 mm	
Relative humidity	Hair Hygrometer		1	-18-38°C db 0-100 % R.H.	1 % 1 %	Not monitored by DAU. Data manually reduced using high altitude psychrometric chart.
A/D data logging	µP controlled analog multiplexing; dual slope digitizer	Doric 220-160-05-34 1 -61-K5-TK1-KK1-31 -53-4K-43-73	1	±11.0 VDC; -165 to +435°C ±1.0 VDC; -40 to 150°C	±(0.03 % R + 0.005 % F + 1.5 µV) Thermo-couple conversion ±0.3°C	Integration of computer and D/A functions should be considered now that such equipment is increasingly available. Provision for digital inputs would be helpful.

4.2.3 Water Flow Rates

Volumetric water flow rates are measured with turbine flow meters, the output signals from which are integrated to obtain the total volume of liquid flow during the period between scans. The meters are calibrated in situ with standard venturi meters placed in the recirculating loop during the calibration as shown in Figure 4-2.

Figure 4-2. Venturi meter used for in-line calibration of turbine meters.

4.2.4 Air Flow Rate

Air flow rate in the central air distribution duct is measured with a vane-type anemometer, seen in the center of the duct on Figure 4-3. The output pulses from the device are summed with a pulse accumulator to obtain the volumetric flow of air in the five minutes between scans. Calibration of the anemometer is accomplished by means of a pitot tube traverse in the duct section immediately upstream of the device.

Figure 4-3. Vane anemometer for air speed measurement placed in a duct. (Heater strips are in foreground, thermopile mounting screen in background.)

4.2.5 Barometric Pressure

Barometric pressure is measured with a Rosemont Series 1332 pressure transducer. The output of this device is periodically checked against a standard mercury barometer.

4.2.6 Mode and Mode Change

The state of the system devices is referred to as the mode. The mode signal originates at the MECA II controller where the mode is determined with the control software. This signal is in the form of a discrete voltage associated with a unique mode. Information about a mode change during the five minutes between scans also originates in the MECA controller. The output signal is 0 or 5V. If the current signal

is different from the previous signal (e.g. 0V then and 5V now) a mode change has occurred. Mode change signals are integrated as well as read instantaneously at the scan. Integrated values show when the mode change occurred.

4.2.7 Integrators

Analog signals from selected transducers are integrated electronically during the interval between scans using AGM integrators. Solar flux, flow rates, electrical energy consumption, and the mode change indicator are integrated. The integrators are reset at the end of each scan.

4.3 Data Acquisition Unit

A Doric Scientific Model 240 data logger and a 7-track Kennedy incremental tape recorder form the basic data acquisition unit. The data logger consists of 100 channels of input, a scanner, multiplexer, analog-to-digital (A/D) converter, crystal driven clock and printer.

The A/D produces 16 bits of information per channel, 11 bits plus sign for the data word plus channel number and unit (voltage or temperature). Maximum input is 10 volts, and resolution is 1 digit (1 millivolt, 0.1 degree temperature). Normal sampling rate is 100 milliseconds per channel when writing only onto tape, but slows to 130 milliseconds per channel when outputting to the microcomputer. The interval between scans is arbitrary and 5 minutes was selected for this application.

4.4 Microcomputer

A Wang Model 2200 microcomputer with 32 thousand bytes of memory was used to process the data in "real" time. Energy quantities and energy balances of primary interest are computed during the period between scans. Although memory capacity and capacity of the peripherals are not large enough to store raw data for 5-minute scans, hourly integrated quantities are stored and archived.

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5.0 DATA PROCESSING

5.1 Data Conversion

Data which require conversion from voltage to physical quantities are generally all linear functions with the exception of emf output from thermopiles. Thus, a slope and offset (intercept) are sufficient for the conversions. For thermopiles, a two-step process is required:

1. Convert T_{ref} to emf, add Δe of the thermopile, corrected to one junction.

2. Convert $e + \Delta e$ to temperature, then subtract the computed temperature from the reference temperature to calculate ΔT .

Third order polynomial relationships for temperature and thermocouple emf as expressed by Equation (5-1) and (5-2) are sufficient for the computations. The coefficients are listed in Table 5-1.

$$e = \sum_{i=1}^3 a_i T^i \quad (5-1)$$

$$T = \sum_{i=1}^3 b_k e^i \quad (5-2)$$

Table 5-1. Polynomial Coefficients for Thermopile Conversions.

Temperature Range	i	a_i	b_i
-50 C to 0 C	1	3.87408×10^1	2.58126×10^{-2}
	2	3.84373×10^{-2}	-7.39074×10^{-7}
	3	2.06663×10^{-5}	1.02788×10^{-10}
0 C to 120 C	1	13.85972×10^1	2.58126×10^{-2}
	2	4.28044×10^{-2}	-6.53650×10^{-7}
	3	-9.96760×10^{-6}	1.94253×10^{-11}

5.2 Calculation of Energy Quantities

Thermal energy flow, Q , which is determined by Equation (5-3):

$$Q = \int \int \dot{m} C_p dT dt \quad (5-3)$$

where

$\dot{m}$ is mass flow rate

C_p is specific heat

T is temperature

t is time,

is approximated by Equation (5-4):

$$Q = \rho C_p (T_2) \left(\frac{\Delta T_2 + T_1}{2} \right) \Delta t \dot{V} \quad (5-4)$$

where

- $\rho C_p (T_2)$ is the product of density and specific heat of fluid as a function of temperature at the current scan.
- ΔT_2 is the temperature difference between two sections at the current scan.
- ΔT_1 is the temperature difference between the same two sections at the last scan.
- Δt is the time interval between scans.
- $\int \dot{V} dt$ is the (electronically) integrated volume of fluid flow between data scans.

In the event that fluid flow has started at some point between scans, calculations are made as follows:

$$Q = \rho C_p (T_2) \Delta T_2 \Delta t_2 \int \dot{V} dt \quad (5-5)$$

where

- Δt_2 is the time interval between start of pump operation and the current scan.

When flow circulation stops,

$$Q = \rho C_p (T_1) \Delta T_1 \Delta t_1 \int \dot{V} dt \quad (5-6)$$

where

- T_1 is the reference fluid temperature at the last scan time.
- Δt_1 is the time interval between the last scan and time the pump stopped.

If there is more than one event between scans, such as a start and stop, or multiple starts and stops, there will be errors in the computation because transient temperatures are involved. Normally, a solar system will not have frequent cycling within a five minute scan, and for operational reasons such cycling should not be allowed because of potential damage to motor driven components.

6.0. SYSTEM PERFORMANCE RESULTS

6.1 Collectors

The advantages of a drain-back system configuration over a double-loop, antifreeze fluid system are: (1) only one collector fluid circulation pump is needed, (2) no heat exchanger is required, and (3) water is used as the heat collecting fluid. A disadvantage is the necessity to pump water against hydrostatic head at start-up. If cycling occurs, pumping energy requirements will increase because water in the collector will drain back into the storage tank. The effect of increased pumping energy at start-up is, however, offset to some extent by recovery of heated water as it returns to storage.

Pumping energy requirement for the collection system was not measured because: (1) pumps in the system were larger than necessary and used because of economy (did not have to purchase a new pump) and convenience, (2) the piping loops to the collector arrays, as shown in Figure 2-9, have longer pipe lengths than in previous configurations tested for Solar House III, and (3) more restriction and fittings are included in experimental systems to accommodate such features as flow meters, temperature fittings, in-line calibration capabilities, and isolation valves to achieve experimental flexibility.

In Figures 6-1 and 6-2 are shown time traces of collector performance for a clear day and for a partly cloudy day. On the clear day, with storage bottom temperature (nearly equal to T_1) at 37 C, the collector pump starts at 08:45 MST, when solar radiation intensity is at 450 W/m^2 and continues to operate until 15:10 MST. Fifteen minutes

Figure 6-1. Representative clear sky solar radiation and collector performance.

Figure 6-2. Solar radiation and collector performance on an intermittently cloudy day.

after shutoff the collector pump starts again and operates for 25 minutes to 15:50 MST. The total operating period was 6 hours 40 minutes. Although not evident in Figure 6-1, the collector pump typically cycles several times at start-up before continuous circulation is maintained. This is because water cools when initially circulated from storage through the pipes and although the water is heated in the collectors, the solar radiation intensity is not sufficient to maintain a temperature difference between the plate and incoming water above the shutoff difference of 2 C (see Section 3.1.4). After several rapid cycles of about 1.5 to 2-minute periods, the pump achieves constant operation. There is cycling during the day when it is partly cloudy as seen in Figure 6-2. Circulation through the collector stopped at 10:55, at 13:00, and at 15:00 MST.

Collector efficiencies during the two example days are also shown on Figures 6-1 and 6-2. The label η_c is for collector efficiency and L and u designate lower and upper arrays (refer to Figure 2-9). The upper collector array appears to be slightly more efficient than the lower array, and the difference is in the piping arrangement, with a standard reverse return for the upper row and direct piping for the lower. However, it is difficult to conclude from the data that a reverse return piping is better because of the condition of several collectors in both rows, as shown in Figures 6-3 and 6-4. Under the circumstances it is surprising to see high collector efficiencies (above 50 percent) for either array.

A graphical presentation of average monthly collector performance is shown in Figure 6-3. Compared to the previous season (Ref. 1),

Figure 6-3. Condensation on collectors due to leaks in the absorber.

Figure 6-4. Close-up view of condensate within the collector.

collector efficiency is lower by about 10 percent, but this is not surprising in view of the condition of the collectors. The data for key performance indicators are summarized in Table 6-1.

6.2 Space Heating

Monthly average daily loads (MJ/day) listed in Table 6-1 are shown graphically on Figure 6-4 and daily measurements are listed in the tables in Appendix B. Compared to previous years, the monthly average daily loads were low in the traditionally colder months. As a consequence, the distribution of monthly average daily loads is nearly uniform over the measurement period.

The contribution to solar energy, to space heating, as well as auxiliary heating by heat pump and electric resistance strips are shown graphically in Figure 6-5. Solar energy supplied 64 percent of the total space heating load for the season, which compares reasonably well with past performance.

6.3 DHW Heating

The contribution to domestic water heating by the solar system was small, less than 50 percent, as shown in Figure 6-6. One reason for this small contribution is the slow recovery rate of the selected heat exchanger. Although the double-wall heat exchanger is sized for use with a DHW system, when large loads are imposed, such as laundry or bathing loads, recovery is slow and auxiliary heating may dominate in a single tank arrangement. The effectiveness of the heat exchanger is about 0.5, and the flow rates used were 8 liters per minute, about the same rate as a stand-alone DHW system with comparable capacity.

Table 6-1. Monthly Mean Daily Quantities of Performance Indicators.

LINE NO.	ITEM	UNITS	DEC	JAN	FEB	MAR	APR	SEASON
1	Days of Data		18	27	27	30	19	121
2	Total Insolation	(MJ/m ² ·day)	13.55	14.61	17.60	15.75	19.33	16.14
3	Insolation while Collecting	(MJ/m ² ·day)	10.40	11.83	13.22	11.28	13.55	12.06
4a	Thermal Energy Collected	(MJ/m ² ·day)	5.29	5.81	6.73	5.51	6.35	5.95
4b	Thermal Energy Collected	(MJ/day)	289.3	317.4	367.7	301.2	347.1	325.1
5	Collector Operating Efficiency	(4a÷3)	0.51	0.49	0.51	0.49	0.47	0.49
6	Collector Daily Efficiency	(4a÷2)	0.39	0.40	0.38	0.35	0.33	0.37
7	Total Heating Load	(MJ/day)	482.2	407.2	436.2	400.1	411.6	423.8
a.	Space Heating Load	(MJ/day)	470.4	343.9	335.1	307.9	317.4	347.7
b.	DHW Heating Load	(MJ/day)	11.8	63.3	101.1	92.2	94.2	76.1
8	Solar Energy Utilized	(MJ/day)	234.5	257.6	309.5	226.6	248.4	256.6
a.	Space Heating Supplied	(MJ/day)	234.5	240.2	257.4	182.7	201.3	222.8
b.	DHW Heating Supplied	(MJ/day)	0.0	17.4	52.1	43.9	47.1	33.8
9	Auxiliary Thermal Energy Utilized	(MJ/day)	247.7	149.7	126.7	173.5	163.2	167.2
a.	Auxiliary Space Heating	(MJ/day)	235.3	103.7	77.7	125.3	116.1	124.8
i.	Heat Pump	(MJ/day)	157.3	100.4	61.2	102.7	78.0	97.2
ii.	Electric Resistance	(MJ/day)	78.6	3.3	16.5	22.6	38.1	27.6
b.	Auxiliary DHW Heating	(MJ/day)	11.8	46.0	49.0	48.2	47.1	42.4
10	Solar Fraction for Total Heating	(8÷7)	0.49	0.63	0.71	0.57	0.60	0.61
a.	Solar Space Heating Fraction	(8a÷7a)	0.50	0.70	0.77	0.59	0.63	0.64
b.	Solar DHW Heating Fraction	(8b÷7b)	0.0	0.27	0.52	0.48	0.50	0.44
11	Solar System Efficiency	8÷(2xAc)	0.32	0.32	0.32	0.26	0.24	0.29

* Values in this table are based on gross collector area of 54.65 m².

Figure 6-5. Collector performance 1982-83 winter heating season
Solar House III.

Figure 6-6. Mean daily energy supplied to load.

Figure 6-7. Monthly average daily space heating loads and proportions supplied by solar, heat pump, and electric resistance heating.

Figure 6-8. Monthly average daily DHW load, solar, and electric resistance contributions.

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7.0 CONCLUSIONS

Although the BNL collectors could not be tested, a drain-back system consisting of Chamberlain collectors was operated through the 1982-83 heating season. From this work it is concluded that:

1. The Chamberlain collectors with absorbers of mild steel have deteriorated over a period of 5 years with substantial leakage from the absorbers. The collectors have been variously wet and dry throughout the period and exposed to the atmosphere because of annual and sometimes semi-annual changes made to the system.
2. The efficiency of the collector decreased about 10 percent from previous years, which is due, at least in part, to leakage from and condensation on the glass covers.
3. Solar contribution to DHW heating was less than 50 percent. When using a single tank system, a slow heat recovery rate for the solar heat exchange coupled with large volume of hot water use at any one time results in use of substantial amounts of auxiliary energy.
4. System efficiency is markedly reduced by storage losses, both by conduction and by vapor migration. Vapor migration to collectors from drain-back systems must be avoided. Conduction losses from pipes, which take place only while collecting, can be reduced by adding more insulation.

8.0 ACKNOWLEDGEMENTS

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9.0 REFERENCES

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APPENDIX A

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Table A-1. Performance of the Chamberlain Collectors in a Drain-Back Solar Heating System in CSU Solar House III during the Month of December 1982.

DAY	TOTAL SOLAR RAD	SOLAR RAD WHILE COLLECT	ENERGY COLLECTED			COLLECTION EFFICIENCY			DAILY EFFICIENCY		
			LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY
13	356.9	247.6	132.1	105.6	237.7	0.53	0.43	0.48	0.37	0.30	0.33
14	473.2	392.9	164.2	159.1	323.4	0.42	0.40	0.41	0.35	0.34	0.34
15	316.2	159.5	100.7	85.0	185.7	0.63	0.53	0.58	0.32	0.27	0.29
16	404.3	127.4	87.0	80.0	167.0	0.68	0.63	0.66	0.22	0.20	0.21
17	360.0	302.6	203.9	154.2	358.1	0.67	0.51	0.59	0.57	0.43	0.50
18	421.6	375.3	187.5	167.6	355.1	0.50	0.45	0.47	0.44	0.40	0.42
19	500.3	448.4	222.1	200.0	422.1	0.50	0.45	0.47	0.44	0.40	0.42
20	432.2	404.3	200.1	135.2	335.2	0.49	0.33	0.41	0.46	0.31	0.39
21	194.9	79.5	47.5	56.0	103.5	0.60	0.70	0.65	0.24	0.29	0.27
22	338.5	275.8	155.7	166.1	321.8	0.56	0.60	0.58	0.46	0.49	0.48
23	164.8	0.0	0.0	0.0	0.0	----	----	----	----	----	----
24	26.8	0.0	0.0	0.0	0.0	----	----	----	----	----	----
25	N O	D A T A									
26	384.3	310.6	167.4	167.4	334.8	0.54	0.54	0.54	0.44	0.44	0.44
27	271.3	197.2	106.0	113.3	219.3	0.54	0.57	0.56	0.39	0.42	0.40
28	551.8	516.4	242.8	250.6	493.3	0.47	0.49	0.48	0.44	0.45	0.45
29	466.2	379.2	197.4	209.6	407.0	0.52	0.55	0.54	0.42	0.45	0.44
30	476.8	413.8	223.2	229.3	452.5	0.54	0.55	0.55	0.47	0.48	0.47
31	524.2	486.6	239.9	250.2	490.1	0.49	0.51	0.50	0.46	0.48	0.47
TOTALS	6664.5	5117.1	2677.6	2529.0	5206.6						
AVG	370.3	284.3	148.8	140.5	289.3	0.52	0.49	0.51	0.40	0.38	0.39

Table A-2. Performance of the Chamberlain Collectors in a Drain-Back Solar Heating System in CSU Solar House III during the Month of January 1983.

DAY	TOTAL SOLAR RAD	SOLAR RAD WHILE COLLECT	ENERGY COLLECTED			COLLECTION EFFICIENCY			DAILY EFFICIENCY		
			LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY
1	520.6	472.9	246.6	261.9	508.5	0.52	0.55	0.54	0.47	0.50	0.49
2	559.1	505.8	228.9	235.8	464.7	0.45	0.47	0.46	0.41	0.42	0.42
3	353.3	235.1	140.2	135.6	275.8	0.60	0.58	0.59	0.40	0.38	0.39
4	502.2	443.9	218.8	224.8	443.6	0.49	0.51	0.50	0.44	0.45	0.44
5	436.7	378.1	194.4	195.3	389.7	0.51	0.52	0.52	0.45	0.45	0.45
6	N O	D A T A									
7	318.5	262.4	131.4	149.7	281.2	0.50	0.57	0.54	0.41	0.47	0.44
8	N O	D A T A									
9	928.9	763.8	380.0	380.0	760.0	0.50	0.50	0.50	0.41	0.41	0.41
10	N O	D A T A									
11	519.2	464.0	219.1	220.0	439.1	0.47	0.47	0.47	0.42	0.42	0.42
12	N O	D A T A									
13	547.1	511.4	197.5	213.5	411.1	0.39	0.42	0.40	0.36	0.39	0.38
14	584.2	453.7	167.6	168.7	336.3	0.37	0.37	0.37	0.29	0.29	0.29
15	317.1	207.5	87.2	90.5	177.7	0.42	0.44	0.43	0.28	0.29	0.28
16	610.1	549.3	245.1	245.5	490.6	0.45	0.45	0.45	0.40	0.40	0.40
17	372.3	280.5	129.9	130.9	260.7	0.46	0.47	0.46	0.35	0.35	0.35
18	294.2	237.3	117.9	120.9	238.7	0.50	0.51	0.50	0.40	0.41	0.41
19	534.8	466.8	172.5	242.9	415.4	0.37	0.52	0.44	0.32	0.45	0.39
20	226.4	174.8	99.7	98.2	197.8	0.57	0.56	0.57	0.44	0.43	0.44
21	39.9	0.0	0.0	0.0	0.0	----	----	----	----	----	----
22	410.8	372.3	182.4	180.4	362.8	0.49	0.48	0.49	0.44	0.44	0.44
23	407.7	369.8	166.7	165.1	331.8	0.45	0.45	0.45	0.41	0.40	0.41
24	541.5	480.2	225.0	219.0	444.0	0.47	0.46	0.46	0.42	0.40	0.41
25	194.1	171.2	82.7	84.2	166.9	0.48	0.49	0.49	0.43	0.43	0.43
26	304.5	185.7	145.6	131.7	277.3	0.78	0.71	0.75	0.48	0.43	0.46
27	155.9	67.8	47.4	54.8	102.3	0.70	0.81	0.75	0.30	0.35	0.33
28	173.7	50.8	34.9	48.6	83.5	0.69	0.96	0.82	0.20	0.28	0.24
29	239.5	91.5	72.0	57.0	129.0	0.79	0.62	0.71	0.30	0.24	0.27
30	621.0	529.5	287.2	294.7	581.9	0.54	0.56	0.55	0.46	0.47	0.47
31	66.4	0.0	0.0	0.0	0.0	----	----	----	----	----	----
TOTALS	10779.5	8726.0	4220.7	4349.8	8570.5						
AVG	399.2	323.2	156.3	161.1	317.4	0.48	0.50	0.49	0.39	0.40	0.40

Table A-3. Performance of the Chamberlain Collectors in a Drain-Back Solar Heating System in CSU Solar House III during the Month of February 1983.

DAY	TOTAL SOLAR RAD	SOLAR RAD WHILE COLLECT	ENERGY COLLECTED			COLLECTION EFFICIENCY			DAILY EFFICIENCY		
			LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY
1	194.1	70.6	32.5	38.1	70.6	0.46	0.54	0.50	0.17	0.20	0.18
2	454.0	315.9	202.4	214.0	416.4	0.64	0.68	0.66	0.45	0.47	0.46
3	494.1	324.9	201.6	190.4	392.0	0.62	0.59	0.60	0.41	0.39	0.40
4	554.4	425.0	216.3	223.0	439.3	0.51	0.52	0.52	0.39	0.40	0.40
5	404.6	282.2	176.1	173.0	349.1	0.62	0.61	0.62	0.44	0.43	0.43
6	569.7	481.0	240.0	240.0	480.0	0.50	0.50	0.50	0.42	0.42	0.42
7	225.0	88.4	36.1	37.6	73.7	0.41	0.42	0.42	0.16	0.17	0.16
8	178.7	63.0	37.9	37.2	75.1	0.60	0.59	0.60	0.21	0.21	0.21
9	465.1	363.1	224.8	222.8	447.6	0.62	0.61	0.62	0.48	0.48	0.48
10	438.9	287.8	177.3	167.4	344.7	0.62	0.58	0.60	0.40	0.38	0.39
11	685.1	613.2	292.1	323.8	615.9	0.48	0.53	0.50	0.43	0.47	0.45
12	641.4	563.3	290.3	308.5	598.8	0.52	0.55	0.53	0.45	0.48	0.47
13	272.4	161.7	84.1	90.3	174.4	0.52	0.56	0.54	0.31	0.33	0.32
14	426.9	287.5	159.1	174.0	333.1	0.55	0.61	0.58	0.37	0.41	0.39
15	NO DATA										
16	230.6	0.0	0.0	0.0	0.0	----	----	----	----	----	----
17	669.8	601.2	301.6	320.4	622.1	0.50	0.53	0.52	0.45	0.48	0.46
18	420.5	268.3	136.7	165.2	301.9	0.51	0.62	0.56	0.33	0.39	0.36
19	582.5	481.3	218.3	231.8	450.1	0.45	0.48	0.47	0.37	0.40	0.39
20	725.0	647.2	299.8	327.4	627.2	0.46	0.51	0.48	0.41	0.45	0.43
21	690.2	575.0	259.7	279.6	539.3	0.45	0.49	0.47	0.38	0.41	0.39
22	686.5	556.6	222.0	240.3	462.3	0.40	0.43	0.42	0.32	0.35	0.34
23	684.3	539.3	207.2	217.9	425.1	0.38	0.40	0.39	0.30	0.32	0.31
24	143.9	0.0	0.0	0.0	0.0	----	----	----	----	----	----
25	630.5	558.0	259.4	279.8	539.2	0.46	0.50	0.48	0.41	0.44	0.43
26	464.8	338.5	167.8	179.0	346.8	0.50	0.53	0.51	0.36	0.39	0.37
27	552.4	463.7	219.3	234.3	453.6	0.47	0.51	0.49	0.40	0.42	0.41
28	502.5	396.0	166.1	183.5	349.5	0.42	0.46	0.44	0.33	0.37	0.35
TOTALS	12988.0	9752.5	4828.4	5099.0	9927.4						
AVG	481.0	361.2	178.8	188.9	367.7	0.50	0.52	0.51	0.37	0.39	0.38

Table A-4. Performance of the Chamberlain Collectors in a Drain-Back Solar Heating System in CSU Solar House III during the Month of March 1983.

DAY	TOTAL SOLAR RAD	SOLAR RAD WHILE COLLECT	ENERGY COLLECTED			COLLECTION EFFICIENCY			DAILY EFFICIENCY		
			LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY
1	392.9	312.9	106.0	122.2	228.2	0.34	0.39	0.36	0.27	0.31	0.29
2	670.9	566.6	250.6	267.2	517.8	0.44	0.47	0.46	0.37	0.40	0.39
3	635.8	540.0	240.0	240.0	480.0	0.44	0.44	0.44	0.38	0.38	0.38
4	9.5	0.0	0.0	0.0	0.0	----	----	----	----	----	----
5	13.7	0.0	0.0	0.0	0.0	----	----	----	----	----	----
6	377.8	283.0	125.6	155.3	280.9	0.44	0.55	0.50	0.33	0.41	0.37
7	742.3	600.1	343.5	363.2	706.7	0.57	0.61	0.59	0.46	0.49	0.48
8	N O	D A T A									
9	718.0	648.3	300.5	332.9	633.4	0.46	0.51	0.49	0.42	0.46	0.44
10	322.9	264.4	106.9	113.6	220.5	0.40	0.43	0.42	0.33	0.35	0.34
11	437.2	353.3	147.1	161.3	308.4	0.42	0.46	0.44	0.34	0.37	0.35
12	416.6	272.7	97.0	111.3	208.3	0.36	0.41	0.38	0.23	0.27	0.25
13	531.2	397.6	196.0	205.7	401.7	0.49	0.52	0.51	0.37	0.39	0.38
14	221.7	108.5	54.4	58.2	112.6	0.50	0.54	0.52	0.25	0.26	0.25
15	165.6	11.7	4.3	2.6	6.9	0.37	0.22	0.30	0.03	0.02	0.02
16	284.4	136.9	70.0	56.8	126.8	0.51	0.41	0.46	0.25	0.20	0.22
17	150.0	0.0	0.0	0.0	0.0	----	----	----	----	----	----
18	106.0	0.0	0.0	0.0	0.0	----	----	----	----	----	----
19	213.3	0.0	0.0	0.0	0.0	----	----	----	----	----	----
20	652.5	461.5	264.8	197.7	462.5	0.57	0.43	0.50	0.41	0.30	0.35
21	854.7	745.4	324.9	365.3	690.2	0.44	0.49	0.46	0.38	0.43	0.40
22	272.7	163.4	49.2	54.6	103.8	0.30	0.33	0.32	0.18	0.20	0.19
23	350.0	64.4	14.0	14.0	28.0	0.22	0.22	0.22	0.04	0.04	0.04
24	362.2	241.5	151.0	132.0	283.0	0.63	0.55	0.59	0.42	0.36	0.39
25	370.3	229.0	136.2	128.6	264.8	0.59	0.56	0.58	0.37	0.35	0.36
26	763.2	645.3	300.7	320.7	621.5	0.47	0.50	0.48	0.39	0.42	0.41
27	771.6	650.0	328.1	334.7	662.8	0.50	0.51	0.51	0.43	0.43	0.43
28	385.7	260.5	145.9	166.0	311.9	0.56	0.64	0.60	0.38	0.43	0.40
29	703.0	580.0	310.9	312.0	622.9	0.54	0.54	0.54	0.44	0.44	0.44
30	803.9	684.3	279.5	314.6	594.1	0.41	0.46	0.43	0.35	0.39	0.37
31	214.2	23.4	77.1	82.7	159.8	3.29	3.53	3.41	0.36	0.39	0.37
TOTALS	12913.9	9245.4	4424.1	4613.3	9037.4						
AVG	430.5	308.2	147.5	153.8	301.2	0.48	0.50	0.49	0.34	0.36	0.35

Table A-5. Performance of the Chamberlain Collectors in a Drain-Back Solar Heating System in CSU Solar House III during the Month of April 1983.

DAY	TOTAL SOLAR RAD	SOLAR RAD WHILE COLLECT	ENERGY COLLECTED			COLLECTION EFFICIENCY			DAILY EFFICIENCY		
			LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY	LOWER ARRAY	UPPER ARRAY	TOTAL ARRAY
1	776.3	640.5	310.4	309.8	620.1	0.48	0.48	0.48	0.40	0.40	0.40
2	308.1	135.5	75.8	73.0	148.7	0.56	0.54	0.55	0.25	0.24	0.24
3	142.2	49.1	21.2	20.2	41.3	0.43	0.41	0.42	0.15	0.14	0.15
4	136.1	43.4	27.7	28.3	56.0	0.64	0.65	0.65	0.20	0.21	0.21
5	365.0	169.5	185.9	76.1	262.0	1.10	0.45	0.77	0.51	0.21	0.36
6	897.3	752.6	358.5	345.7	704.2	0.48	0.46	0.47	0.40	0.39	0.39
7	856.6	721.7	326.2	344.3	670.5	0.45	0.48	0.46	0.38	0.40	0.39
8	771.6	652.5	306.6	324.6	631.2	0.47	0.50	0.48	0.40	0.42	0.41
9	N O	D A T A									
10	381.2	268.5	114.7	144.7	259.4	0.43	0.54	0.48	0.30	0.38	0.34
11	239.0	161.5	91.0	73.3	164.3	0.56	0.45	0.51	0.38	0.31	0.34
12	163.4	43.4	5.8	3.4	9.2	0.13	0.08	0.11	0.04	0.02	0.03
13	336.0	201.9	73.4	73.9	147.3	0.36	0.37	0.36	0.22	0.22	0.22
14	790.5	681.0	300.8	354.3	655.1	0.44	0.52	0.48	0.38	0.45	0.41
15	426.0	362.2	153.0	173.6	326.6	0.42	0.48	0.45	0.36	0.41	0.38
16	702.1	540.7	249.5	277.7	527.2	0.46	0.51	0.49	0.36	0.40	0.38
17	798.9	663.4	266.3	321.9	588.2	0.40	0.49	0.44	0.33	0.40	0.37
18	696.0	555.8	210.2	229.9	440.1	0.38	0.41	0.40	0.30	0.33	0.32
19	675.1	322.1	140.7	146.0	286.7	0.44	0.45	0.45	0.21	0.22	0.21
20	573.3	76.5	32.6	24.1	56.6	0.43	0.31	0.37	0.06	0.04	0.05
TOTALS	10034.9	7041.6	3250.0	3344.7	6594.7						
AVG	528.2	370.6	171.1	176.0	347.1	0.46	0.47	0.47	0.32	0.33	0.33

APPENDIX B

PAGES 51 to 52
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Table B-1. Performance of a Drain-Back Solar Heating System in CSU Solar House III for the Month of December 1982.

DAY	ENERGY COLLECTED	ENERGY INTO STORE	ENERGY OUT OF STORE	SPACE HEATING					DHW HEATING			
				SOLAR	HEAT PUMP	ELEC AUX	TOTAL	SOLAR FRACTION	SOLAR	ELEC AUX	TOTAL	SOLAR FRACTION
13	237.7	218.6	244.4	255.5	0.0	48.3	303.8	0.84	0.0	0.0	0.0	0.00
14	323.4	362.8	270.0	282.1	52.7	0.0	334.9	0.84	0.0	0.0	0.0	0.00
15	185.7	217.2	163.7	173.9	0.0	0.0	173.9	1.00	0.0	0.0	0.0	0.00
16	167.0	80.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.00
17	358.1	324.5	222.0	231.7	0.0	0.0	231.7	1.00	0.0	0.0	0.0	0.00
18	355.1	341.7	371.6	393.9	405.8	147.1	946.8	0.42	0.0	0.0	0.0	0.00
19	422.1	233.8	279.8	287.6	186.2	28.7	502.5	0.57	0.0	0.0	0.0	0.00
20	335.2	350.1	186.8	0.0	300.0	12.3	312.3	0.00	0.0	0.0	0.0	0.00
21	103.5	84.1	223.0	234.8	0.0	0.0	234.8	1.00	0.0	0.0	0.0	0.00
22	321.8	300.0	288.9	302.0	28.9	8.4	339.2	0.89	0.0	0.0	0.0	0.00
23	0.0	89.9	0.0	0.0	512.1	50.8	562.8	0.00	0.0	0.0	0.0	0.00
24	0.0	89.9	49.3	52.0	153.8	161.3	367.1	0.14	0.0	0.0	0.0	0.00
25	N O D A T A											
26	334.8	328.7	251.7	262.3	324.6	36.3	623.2	0.42	0.0	0.0	0.0	0.00
27	219.3	218.7	160.2	168.5	340.3	290.8	799.5	0.21	0.0	0.0	0.0	0.00
28	493.3	501.1	380.6	399.0	171.9	179.8	750.7	0.53	0.0	46.8	46.8	0.00
29	407.0	411.7	298.9	311.9	157.3	146.5	615.7	0.51	0.0	23.4	23.4	0.00
30	452.5	453.3	382.4	402.3	107.3	204.2	713.8	0.56	0.0	105.5	105.5	0.00
31	490.1	480.4	440.1	462.9	91.0	100.1	654.0	0.71	0.0	36.0	36.0	0.00
TOTALS	5206.6	5086.4	4213.3	4220.4	2831.8	1414.6	8466.8		0.0	211.7	211.7	
AVG	289.3	282.6	234.1	234.5	157.3	78.6	470.4	0.50	0.0	11.8	11.8	0.00

Table B-2. Performance of a Drain-Back Solar Heating System in CSU Solar House III for the Month of January 1983.

DAY	ENERGY COLLECTED	ENERGY INTO STORE	ENERGY OUT OF STORE	SPACE HEATING					DHW HEATING			
				SOLAR	HEAT PUMP	ELEC AUX	TOTAL	SOLAR FRACTION	SOLAR	ELEC AUX	TOTAL	SOLAR FRACTION
1	508.5	522.7	401.7	411.2	56.6	3.0	470.8	0.87	0.0	36.0	36.0	0.00
2	464.7	462.6	525.6	551.7	0.0	0.0	551.7	1.00	0.0	36.0	36.0	0.00
3	275.8	275.8	231.3	247.2	48.9	0.0	296.1	0.83	0.0	33.1	33.1	0.00
4	443.6	471.5	265.3	275.1	43.0	0.0	318.1	0.86	0.0	46.8	46.8	0.00
5	389.7	414.2	141.7	147.2	0.0	0.0	147.2	1.00	0.0	30.6	30.6	0.00
6	N O	D A T A										
7	281.2	292.2	122.6	126.1	0.0	0.0	126.1	1.00	0.1	34.2	34.3	0.00
8	N O	D A T A										
9	760.0	760.0	580.0	569.4	183.8	28.0	781.3	0.73	0.0	32.4	32.4	0.00
10	N O	D A T A										
11	439.1	460.0	440.0	38.2	0.0	0.0	38.2	1.00	8.7	38.9	47.6	0.18
12	N O	D A T A										
13	411.1	424.5	127.3	134.8	0.0	0.0	134.8	1.00	18.6	39.2	57.9	0.32
14	336.3	343.1	283.8	284.7	0.0	0.0	284.7	1.00	39.9	12.6	52.5	0.76
15	177.7	182.9	438.1	454.1	0.0	0.0	454.1	1.00	1.5	12.6	14.1	0.10
16	490.6	514.3	414.2	427.8	0.0	0.0	427.8	1.00	9.1	12.6	21.7	0.42
17	260.7	270.4	272.4	280.5	0.0	0.0	280.5	1.00	36.4	54.0	90.4	0.40
18	238.7	256.0	276.6	295.8	9.3	0.0	305.1	0.97	30.3	56.2	86.4	0.35
19	415.4	448.4	278.8	296.0	31.7	0.0	327.7	0.90	53.5	62.6	116.2	0.46
20	197.8	206.7	267.3	285.1	115.3	0.0	400.4	0.71	22.1	54.0	76.1	0.29
21	0.0	0.0	0.0	0.0	385.1	31.5	416.6	0.00	16.0	63.0	79.0	0.20
22	362.8	380.7	285.4	299.7	188.5	14.0	502.2	0.60	24.1	55.8	79.9	0.30
23	331.8	350.9	302.4	316.5	210.1	12.3	538.9	0.59	23.8	55.8	79.6	0.30
24	444.0	238.5	45.4	44.8	42.0	0.0	86.8	0.52	21.6	55.8	77.4	0.28
25	166.9	169.4	143.1	155.1	134.3	0.0	289.4	0.54	17.4	59.8	77.1	0.23
26	277.3	265.7	188.9	202.4	133.2	0.0	335.6	0.60	25.5	73.4	99.0	0.26
27	102.3	110.3	52.1	57.1	249.5	0.0	306.6	0.19	20.1	61.2	81.3	0.25
28	83.5	87.7	0.0	0.0	261.8	0.0	261.8	0.00	21.1	66.6	87.7	0.24
29	129.0	116.3	94.0	100.5	381.6	0.0	482.1	0.21	15.4	55.8	71.2	0.22
30	581.9	603.5	352.4	368.4	50.5	0.0	418.9	0.88	48.3	48.6	96.9	0.50
31	0.0	0.0	110.7	117.1	185.3	0.0	302.4	0.39	15.1	54.0	69.1	0.22
TOTALS	8570.5	8628.0	6641.0	6486.4	2710.4	88.9	9285.7		468.5	1241.7	1710.2	
AVG	317.4	319.6	246.0	240.2	100.4	3.3	343.9	0.70	17.4	46.0	63.3	0.27

Table B-3. Performance of a Drain-Back Solar Heating System in CSU Solar House III for the Month of February 1983.

DAY	ENERGY COLLECTED	ENERGY INTO STORE	ENERGY OUT OF STORE	SPACE HEATING					DHW HEATING			
				SOLAR	HEAT PUMP	ELEC AUX	TOTAL	SOLAR FRACTION	SOLAR	ELEC AUX	TOTAL	SOLAR FRACTION
1	70.6	76.4	0.0	0.0	340.4	0.0	340.4	0.00	18.6	59.4	78.0	0.24
2	416.4	422.0	308.4	325.3	87.4	59.8	472.5	0.69	34.8	70.2	105.0	0.33
3	392.0	380.6	292.5	309.2	110.6	75.4	495.2	0.62	30.3	63.0	93.3	0.33
4	439.3	452.1	391.4	411.0	57.7	51.6	520.3	0.79	28.8	72.0	100.8	0.29
5	349.1	342.9	270.4	287.2	253.1	126.5	666.8	0.43	0.0	72.0	72.0	0.00
6	480.0	460.0	131.4	131.4	64.4	21.2	217.0	0.61	0.0	36.0	36.0	0.00
7	73.7	142.1	226.9	243.5	142.8	33.6	419.9	0.58	0.0	57.6	57.6	0.00
8	75.1	70.3	0.0	0.0	399.3	12.1	411.4	0.00	21.5	59.4	80.9	0.27
9	447.6	457.4	291.6	305.9	54.1	0.0	360.0	0.85	45.7	66.6	112.3	0.41
10	344.7	365.2	272.8	287.2	0.0	0.0	287.2	1.00	41.8	57.6	99.4	0.42
11	615.9	604.2	423.7	444.4	0.0	0.0	444.4	1.00	52.2	47.5	99.7	0.52
12	598.8	589.0	309.5	322.4	0.0	0.0	322.4	1.00	60.8	47.9	108.7	0.56
13	174.4	164.0	263.0	278.6	0.0	0.0	278.6	1.00	32.6	46.8	79.4	0.41
14	333.1	329.4	248.5	263.9	0.0	0.0	263.9	1.00	45.8	55.8	101.6	0.45
15	N O D A T A											
16	0.0	214.2	171.0	180.4	114.4	64.0	358.7	0.50	21.2	68.4	89.6	0.24
17	622.1	620.3	229.4	232.8	27.8	0.0	260.5	0.89	72.3	61.2	133.5	0.54
18	301.9	313.4	147.7	151.8	0.0	0.0	151.8	1.00	68.5	47.9	116.4	0.59
19	450.1	424.0	427.7	451.4	0.0	0.0	451.4	1.00	52.8	38.5	91.3	0.58
20	627.2	636.6	348.6	368.8	0.0	0.0	368.8	1.00	73.4	36.0	109.4	0.67
21	539.3	537.2	179.2	177.5	0.0	0.0	177.5	1.00	117.1	28.8	145.9	0.80
22	462.3	453.2	135.3	153.0	0.0	0.0	153.0	1.00	134.2	14.4	148.6	0.90
23	425.1	405.7	146.4	158.1	0.0	0.0	158.1	1.00	140.0	10.1	150.0	0.93
24	0.0	0.0	277.9	291.9	0.0	0.0	291.9	1.00	59.3	42.1	101.4	0.58
25	539.2	542.3	324.3	332.4	0.0	0.0	332.4	1.00	74.6	37.8	112.4	0.66
26	346.8	342.2	338.4	347.5	0.0	0.0	347.5	1.00	49.0	41.4	90.4	0.54
27	453.6	458.7	279.5	286.5	0.0	0.0	286.5	1.00	64.1	37.8	101.9	0.63
28	349.5	346.0	196.4	209.1	0.0	0.0	209.1	1.00	66.8	46.8	113.6	0.59
TOTALS	9927.4	10149.3	6631.7	6950.9	1651.9	444.2	9047.0		1406.0	1323.0	2729.0	
AVG	367.7	375.9	245.6	257.4	61.2	16.5	335.1	0.77	52.1	49.0	101.1	0.52

Table B-4. Performance of a Drain-Back Solar Heating System in CSU Solar House III for the Month of March 1983.

DAY	ENERGY COLLECTED	ENERGY INTO STORE	ENERGY OUT OF STORE	SPACE HEATING					DHW HEATING			
				SOLAR	HEAT PUMP	ELEC AUX	TOTAL	SOLAR FRACTION	SOLAR	ELEC AUX	TOTAL	SOLAR FRACTION
1	228.2	224.0	105.8	109.0	0.0	0.0	109.0	1.00	65.6	48.6	114.2	0.57
2	517.8	521.7	142.0	148.9	0.0	0.0	148.9	1.00	108.7	28.8	137.5	0.79
3	480.0	488.9	111.0	118.3	0.0	0.0	118.3	1.00	136.7	12.6	149.3	0.92
4	0.0	0.0	0.0	0.0	240.0	0.0	240.0	0.00	6.0	24.5	30.5	0.20
5	0.0	0.0	202.6	218.2	100.6	0.0	318.8	0.68	10.6	46.1	56.6	0.19
6	280.9	279.5	231.4	245.9	170.6	0.0	416.5	0.59	18.2	45.7	63.9	0.28
7	706.7	710.5	211.4	214.7	13.4	0.0	228.1	0.94	85.3	49.3	134.6	0.63
8	NO DATA											
9	633.4	631.1	85.0	88.6	0.0	0.0	88.6	1.00	33.5	56.5	90.0	0.37
10	220.5	213.6	0.0	80.0	0.0	0.0	80.0	1.00	29.5	38.9	68.4	0.43
11	308.4	317.0	94.1	98.7	0.0	0.0	98.7	1.00	108.7	10.8	119.5	0.91
12	208.3	237.1	160.0	169.0	0.0	0.0	169.0	1.00	47.5	30.6	78.1	0.61
13	401.7	372.3	141.6	155.3	0.0	0.0	155.3	1.00	64.5	28.8	93.3	0.69
14	112.6	110.1	251.0	259.6	0.0	0.0	259.6	1.00	44.2	38.5	82.8	0.53
15	6.9	45.0	222.9	238.2	101.1	0.0	339.3	0.70	22.7	57.6	80.3	0.28
16	126.8	106.9	0.0	0.0	325.5	117.9	443.4	0.00	24.0	62.3	86.3	0.28
17	0.0	0.0	0.0	0.0	403.9	137.5	541.3	0.00	16.4	67.7	84.0	0.19
18	0.0	0.0	0.0	0.0	375.1	87.5	462.6	0.00	14.8	67.3	82.2	0.18
19	0.0	0.0	0.0	0.0	458.6	92.5	551.2	0.00	11.5	52.9	64.4	0.18
20	462.5	342.4	215.3	225.8	175.1	75.6	476.5	0.47	25.4	52.6	78.0	0.33
21	690.2	507.1	372.6	385.0	0.0	20.1	405.1	0.95	61.0	56.5	117.5	0.52
22	103.8	110.0	197.3	208.7	139.6	20.1	368.4	0.57	22.1	70.2	92.3	0.24
23	28.0	28.9	176.2	186.7	134.2	40.9	361.8	0.52	0.0	55.8	55.0	0.00
24	283.0	253.7	135.4	215.0	116.9	0.0	331.8	0.65	30.4	64.8	95.2	0.32
25	264.8	280.1	201.9	145.2	207.4	55.4	408.0	0.36	23.9	66.6	90.5	0.26
26	621.5	604.8	509.7	529.3	44.1	29.7	603.1	0.88	35.1	49.0	84.1	0.42
27	662.8	653.1	435.3	447.4	31.1	0.0	478.6	0.93	41.0	37.4	78.5	0.52
28	311.9	301.1	224.2	233.8	43.3	0.0	277.1	0.84	39.6	63.0	102.6	0.39
29	622.9	599.6	337.3	344.2	0.0	0.0	344.2	1.00	57.2	60.5	117.7	0.49
30	594.1	595.5	127.3	128.6	0.0	0.0	128.6	1.00	85.4	49.3	134.7	0.63
31	159.8	142.3	274.7	285.5	0.0	0.0	285.5	1.00	48.4	54.0	102.4	0.47
TOTALS	9037.4	8676.1	5165.6	5479.6	3080.5	677.2	9237.3		1317.6	1447.2	2764.8	
AVG	301.2	289.2	172.2	182.7	102.7	22.6	307.9	0.59	43.9	48.2	92.2	0.48

Table B-5. Performance of a Drain-Back Solar Heating System in CSU Solar House III for the Month of April 1983.

	ENERGY DAY COLLECTED	ENERGY INTO STORE	ENERGY OUT OF STORE	SPACE HEATING					DHW HEATING			
				SOLAR	HEAT PUMP	ELEC AUX	TOTAL	SOLAR FRACTION	SOLAR	ELEC AUX	TOTAL	SOLAR FRACTION
1	620.1	625.5	354.2	359.4	0.0	6.7	366.1	0.98	65.0	46.8	111.8	0.58
2	148.7	138.9	306.0	323.5	155.3	0.0	478.8	0.68	15.6	37.8	53.4	0.29
3	41.3	56.3	0.0	0.0	438.3	147.0	585.3	0.00	17.9	57.6	75.5	0.24
4	56.0	45.6	0.0	0.0	320.9	157.7	478.6	0.00	18.3	61.2	79.5	0.23
5	262.0	481.5	274.6	289.3	89.0	85.6	463.9	0.62	31.7	72.0	103.7	0.31
6	704.2	735.7	426.6	431.4	21.4	0.0	452.8	0.95	56.1	48.6	104.7	0.54
7	670.5	675.4	78.4	71.7	0.0	0.0	71.7	1.00	24.5	49.7	74.2	0.33
8	631.2	639.9	13.2	13.3	0.0	0.0	13.3	1.00	17.8	39.6	57.4	0.31
9	N O D A T A											
10	259.4	247.2	248.3	253.9	0.0	0.0	253.9	1.00	46.9	36.0	82.9	0.57
11	164.3	158.5	214.7	218.6	0.0	0.0	218.6	1.00	48.3	41.4	89.7	0.54
12	9.2	26.2	210.7	225.2	145.5	64.3	434.9	0.52	20.2	56.9	77.1	0.26
13	147.3	140.3	108.4	113.8	296.2	148.2	558.1	0.20	20.0	64.8	84.8	0.24
14	655.1	683.8	309.4	310.8	15.4	0.0	326.2	0.95	63.9	55.8	119.7	0.53
15	326.6	357.9	272.5	281.4	0.0	0.0	281.4	1.00	60.0	54.0	114.0	0.53
16	527.2	532.8	298.1	296.0	0.0	0.0	296.0	1.00	53.2	34.9	88.1	0.60
17	588.2	582.9	230.5	236.1	0.0	0.0	236.1	1.00	69.4	34.2	103.6	0.67
18	440.1	445.7	0.0	200.0	0.0	11.3	211.3	0.95	93.0	37.1	130.1	0.71
19	286.7	291.3	0.0	200.0	0.0	0.0	200.0	1.00	91.3	31.3	122.6	0.74
20	56.6	51.2	0.0	0.0	0.0	103.1	103.1	0.00	81.7	36.0	117.7	0.69
TOTALS	6594.7	6916.3	3345.6	3824.4	1481.7	723.9	6030.1		894.9	895.7	1790.6	
AVG	347.1	364.0	176.1	201.3	78.0	38.1	317.4	0.63	47.1	47.1	94.2	0.50