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EVALUATION OF HIGH PERFORMANCE EVACUATED TUBULAR COLLECTORS IN A RESIDENTIAL HEATING AND COOLING SYSTEM: COLORADO STATE UNIVERSITY SOLAR HOUSE I

Report for Period October 1, 1976—September 30, 1977

By
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March 1978

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Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado

U.S. Department of Energy

Solar Energy

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for the NATO Committee on the Challenges of Modern Society

Prepared by

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1. General Description of System Project and Environment

CSU Solar House I is configured with a prototype Corning evacuated tubular collector and a new Arkla lithium bromide water chiller designed for solar operation. Data have been collected for this configuration since January 1977. Prior to that time and since mid-1974, Solar House I has operated with a flat-plate collector and a previous Arkla LiBr air conditioner modified to operate in the lower solar temperature ranges.

Project objectives were to develop an operating and control system for the new configuration and to compare the performance of the new residential solar heating, cooling, and hot water system with performance of the previous system. Many problems were encountered in the evolution of the operating and control systems due to the different operating characteristics of evacuated tubular collectors, such as their rapid thermal response and the possibility of much higher temperatures as compared to a flat-plate collector.

1.1 Environment

1.1.1. Climate

The climate of the region is semi-arid with continental winter and meager summer rainfall. The average annual precipitation is 36.3 cm (14.3 in), consisting of 24.9 cm (9.8 in) rainfall and 11.4 cm (4.5 in) snowfall. The Trewartha climate designation is classified as BSk (dry, semi-arid [steppe], middle latitude)[1].

[1] G.T. Trewartha, An Introduction to Climate, McGraw-Hill, New York, 1954.

1.1.2. Location

Fort Collins, Colorado is 96.6 kilometers (60 miles) north of Denver, Colorado and the Solar Village is located 6.4 kilometers (4 miles) west of the city center on the Foothills Research Campus of Colorado State University. The latitude of the Solar Village is 40.6°N, the longitude is 105.1°W of the principal meridian, and the elevation is 1585 meters (5200 ft) above sea level. The Solar Houses are on the south slope of a hill, about 60 meters (200 ft) above the level of the city of Fort Collins, and the air is generally clear of local air pollution effects. The front range of the Rocky Mountains begins approximately one kilometer (0.6 mile) to the west and rises to the Continental Divide, which is 50 kilometers (31 miles) farther to the west. Eastward from the site of the Solar Village is generally flat.

1.1.3. Solar Radiation

Percentage of maximum possible annual sunshine hours is 67 percent (computed over 57-year period). The mean monthly global (total) insolation on a plane tilted toward the south at a 45 degree angle is tabulated in Table 1. Except where noted, the data were obtained during the period of this report (1 October 1976 to 30 September 1977) by the use of an Eppley Precision Spectral Pyranometer.

1.1.4. Ambient Temperature

The high temperatures during summer months are generally below 40°C (104°F) and low temperatures during the winter months are generally above -30°C (-22°F). The average daily temperature in January is -3°C (26°F) and in July it is 21°C (69.5°F) [2]. The mean daily temperature

[2] Meteorological Data, 1887-1957, Bulletin 509-S, Agricultural Experiment Station, Colorado State University, Fort Collins, Colorado

Table 1

Monthly Average Climatological Condition

Month	Solar Insolation		Ambient Temperature		Wind speed m/sec
	Langleys/day	MJ/M^2-day	day bulb °C	dew point* °C	
October	457	19.1	8.4	-0.4	2.37
November	356	14.9	5.7	-6.6	2.63
December	348	14.6	2.2	-9.8	2.66
January	381	16.0	-4.0	-11.2	2.87
February	336	14.1	3.2	-9.8	2.93
March	430	18.0	3.9	-6.5	3.34
April	382	16.0	9.0	-1.7	3.49
May	407*	17.0*	12.5*	4.1	2.95
June	460*	19.3*	17.8*	9.3	2.41
July	493*	20.6*	23.7*	12.4	2.11
August	459	19.2	20.5	11.4	2.05
September	554	23.2	20.0	6.1	2.17

*Based on data from previous years

is tabulated in Table 1. Except where noted, the data were obtained during the period of this report using a type T thermocouple mounted in a radiation shield two meters above the ground with a fan circulating outside air across the sensor.

The mean annual heating degree days (18.3°C or 65°F) are 3500°C-days per year (6300°F-days per year). The mean annual cooling degree days (23.9°C or 75°F base) are 278°C-days per year (500°F-days per year). Design temperatures are -23°C (-10°F) for winter and 35°C (95°F) dry bulb, 18°C (64°F) wet bulb for the summer.

1.1.5. Wind

Average monthly wind speed is tabulated in Table 1 [3]. These data were obtained using a cup anemometer mounted 65 feet above the ground over a 70-year period. The prevailing winds are from the northwest and occur primarily in the spring and fall. Gusts of 36 m/sec (80 mph) are common and 54 m/sec (120 mph) gusts occur occasionally.

1.2 Description of System

1.2.1. Qualitative Description

The solar heating and cooling system was installed in a residence-type building at a site on the Foothills Campus of Colorado State University in Fort Collins, Colorado. Photograph 1 shows a view of the building from the southeast shortly after it was completed. The building is a modern three-bedroom frame residence with a living area of 140 square meters (1500 sq ft) and a full, heated basement, the south wall of which is entirely above grade. The design heating load was computed to be 16.1 kilowatts at -23°C (55,000 Btu/hr at - 10°F; corresponding to 17,600 Btu/°F-day). The design cooling load is approximately 10.5 kilowatts (3 tons or 36,000 Btu/hr). The insulation was typical, with 8.9 cm (3.5 inches) fiberglass in the walls (R = 6.85°Cm^2/w; 12 hr-°F-Ft^2/Btu) and 14 cm (5.5 inches) of fiberglass in the ceiling (R = 10.85°Cm^2w; 19 Hr-°F-Ft^2/Btu).

The solar heating and cooling system includes the conventional components such as lithium bromide absorption cooling unit with cool storage, hot water boiler; air heater/cooler coil, hot water heater, and associated piping, ducts and pumps, and the solar components,

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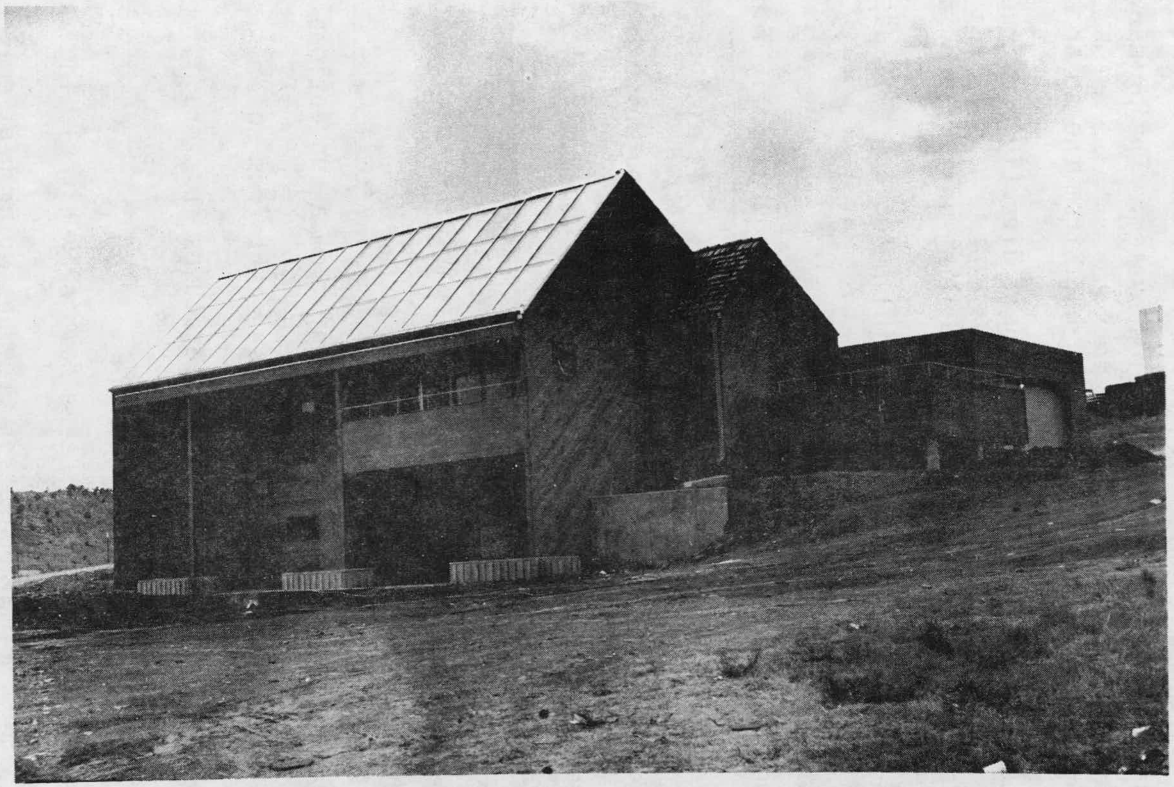
[3]Ob. cit., Meteorological Data, 1887-1957



Photograph 1. Colorado State University Solar House I

consisting of a solar collector and pump, thermal storage with heat exchanger and hot water preheat tank and an automatic valve. Figures 1 and 2 are cross section schematic diagrams of the installation which shows all of the components except the collector and associated piping, the control sensors, and the air distribution system. The primary modes of solar heat collection are: storing heat from the solar collector via a heat exchanger, and storing heat directly from the solar collector. Energy to the heating and cooling unit is provided either by use of hot water from storage, if the temperature is adequate, or from the auxiliary boiler as necessary.

The house hot water system utilizes solar energy directly for preheating service hot water using a tube and shell heat exchanger. Water from a cold water main enters the preheat tank, to which heat is supplied directly from the solar collectors by pumped circulation through the heat exchanger. On demand, the preheated water then flows to a conventional gas hot water heater, which maintains the required temperatures.

This heat exchanger location is different from a conventional design where energy is supplied to the preheat tank from solar storage. The change was made to maintain higher temperatures in storage during summer operation of the water chiller.

Because of the possibility of freeze damage by circulating water through the collector, normal operation provides solar heat collection in a 50 percent solution of ethylene glycol (commercial automotive anti-freeze) in water. The cost of several hundred gallons of glycol in the main storage system would be prohibitive, so a heat exchanger (a series of two tube and shell units) is employed for transfer of heat from the

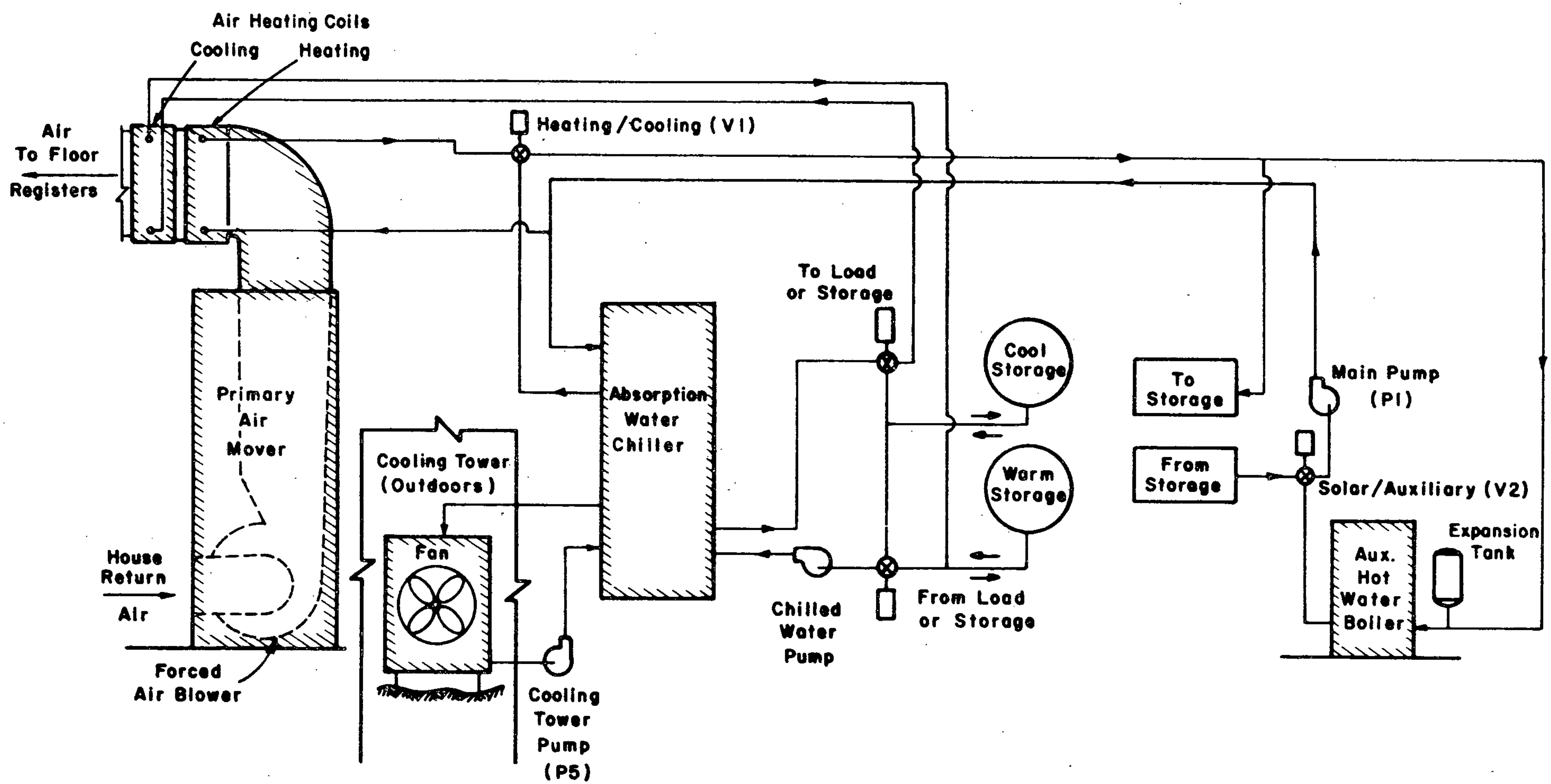


Figure 1. Solar House I Heating - Air Conditioning - Hot Water Equipment

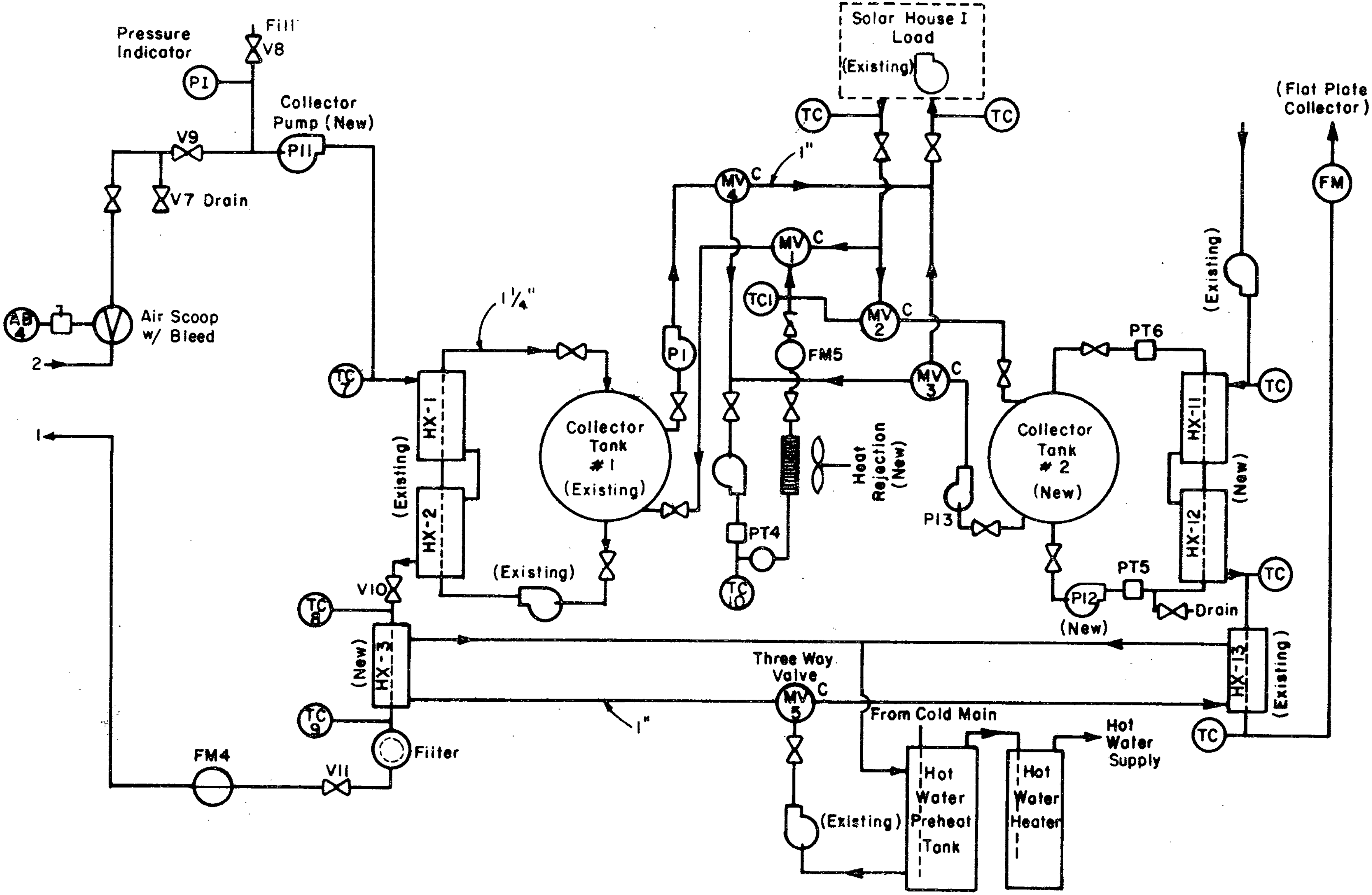


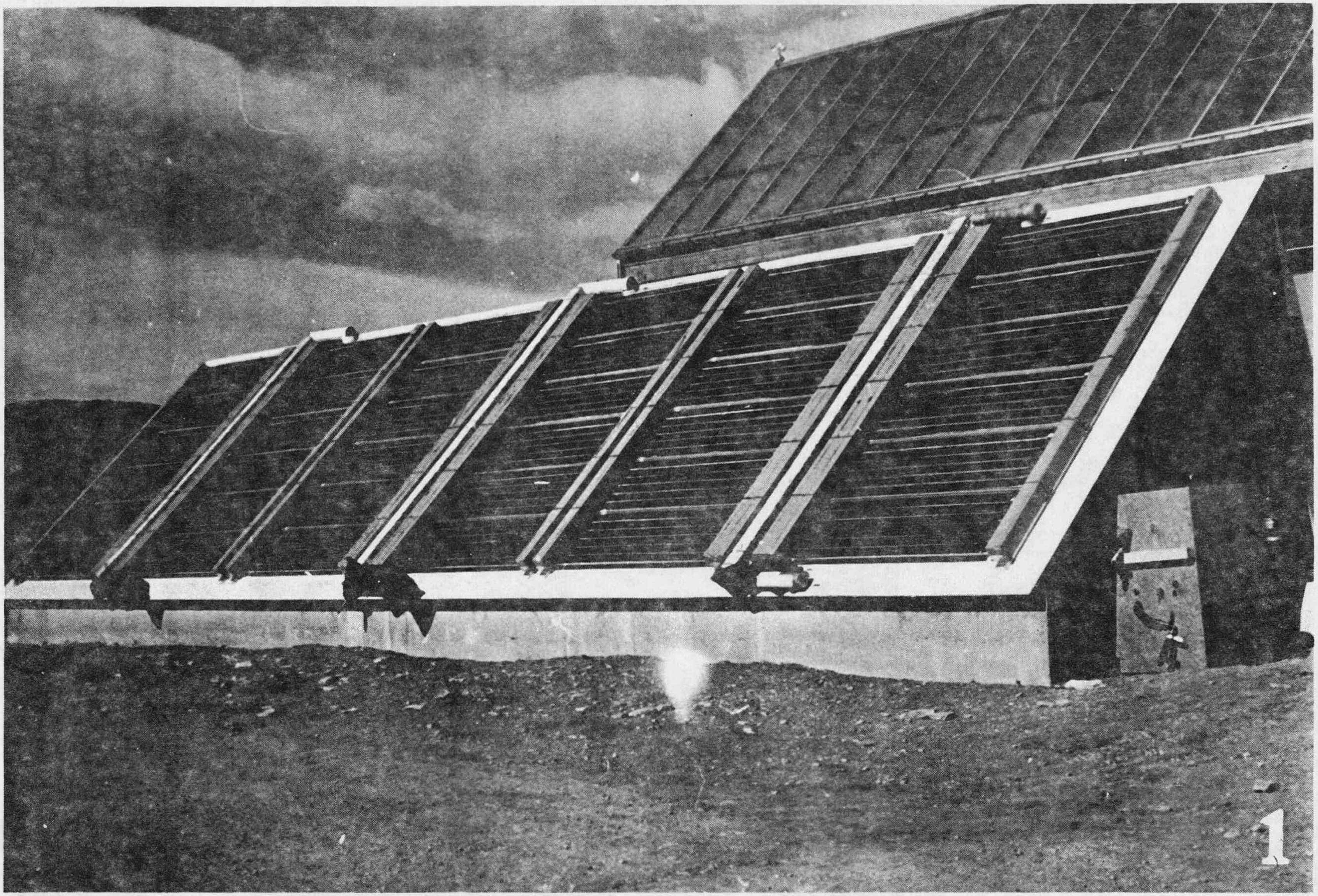
Figure 2. Solar House I: Collector Test Bed - Flow Diagram December 16, 1976

small volume of collector fluid (about 106 liters, 28 gallons) to a large volume of water comprising the thermal storage.

Solar House I actually has two complete solar collector and storage subsystems. As shown in Photograph 2, the original flat-plate collectors are roof-mounted and the Corning evacuated tube collector is mounted on a test bed immediately south of the house. Either collector system can be connected to the house load. During the data collection period covered by this report, the house load was connected primarily to a test bed-mounted Corning evacuated tubular collector and the flat-plate collector system was connected to an equivalent house load generated by a computer program.

Figure 3 details the interface between flat-plate collector panels and the rest of the solar system. The collector absorber panels are made of aluminum, and to avoid galvanic corrosion they are not directly connected to the copper piping in the solar system. Rubber hose connections between the copper and aluminum piping accomplish this separation. A filter and aluminum screen "getter" (sacrificial) are also used to minimize corrosion risk.

A 113 liter (30 gallon) vented surge tank is installed on the outlet side of the collector. This tank provides volume for liquid expansion and also permits boiling to occur in the collector without pressure build-up. If the collector pump fails, boiling results in some liquid loss, but the surge tank can refill the system automatically when operation resumes.



Photograph 2. Corning Evacuated Tube Collector Mounted on Test Bed and Solar House I Liquid Flat Plate Collector Mounted on Roof

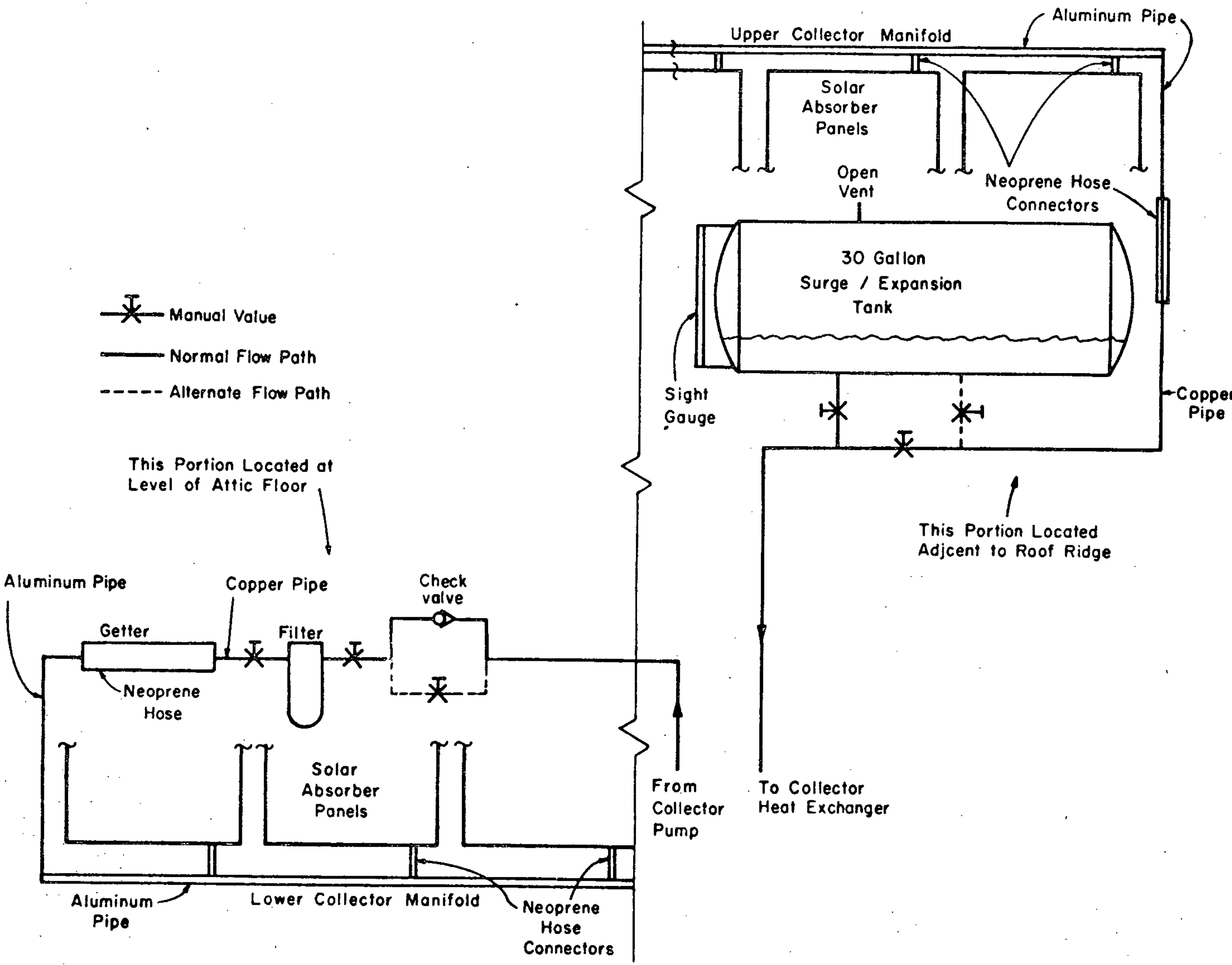


Figure 3. Diagram of Piping at Collector Inlet and Outlet (in attic)

The storage container is a phenolic-lined horizontal steel cylinder 3.35 meters (11 feet) long and 1.22 meters (4 feet) in diameter. It holds 4275 liters (1131 gallons), a nominal 61 liters/m^2 of collector (1.5 gallons/ft^2). During the period of this report, the tank was covered by two layers of bonded glass batt insulation having an R factor of 17.7 °Cm^2/w (R = 30.4 Hr-Ft^2-°F/Btu).

Figure 4 details the piping schematic for the Corning collectors. The cooling fluid in this array is maintained at a positive pressure of 185 kPa (15 psig), which induces a boiler point of 118°C (245°F). Make-up fluid is provided by three 20-liter (5 gallon) expansion tanks, and overpressure is prevented by three pressure relief valves set at 3.04 atmospheres (30 psig).

The storage container is a light gauge vertical galvanized steel cylinder 1.83 meters (6 ft) high and 1.68 meters (5.5 ft) in diameter. It holds 4275 liters (1131 gallons), a nominal 61 liters/m^2 of collector (1.5 gallons/ft^2). During the first year of operation and during the data collection period covered by this report, the tank was covered by a nominal 10 centimeters (4 in) of cellulose insulation having a theoretical R factor of 17.14 °Cm^2/w (R = 30 Hr-Ft^2-°F/Btu).

Figure 4 shows the piping interface between the flat-plate and the evacuated tubular collectors. The collector array not connected to the house load rejects heat to ambient through a heat exchanger. The rejection rate is computer controlled to generate an equivalent heat load to that measured in Solar House I. Table 2 lists the components labeled in Figures 3 and 4 and their specifications.

1.2.2. Quantitative Description

1.2.2.1. Solar System -- The flat-plate collector system designed to furnish 75 percent of the space heating and 75 percent of

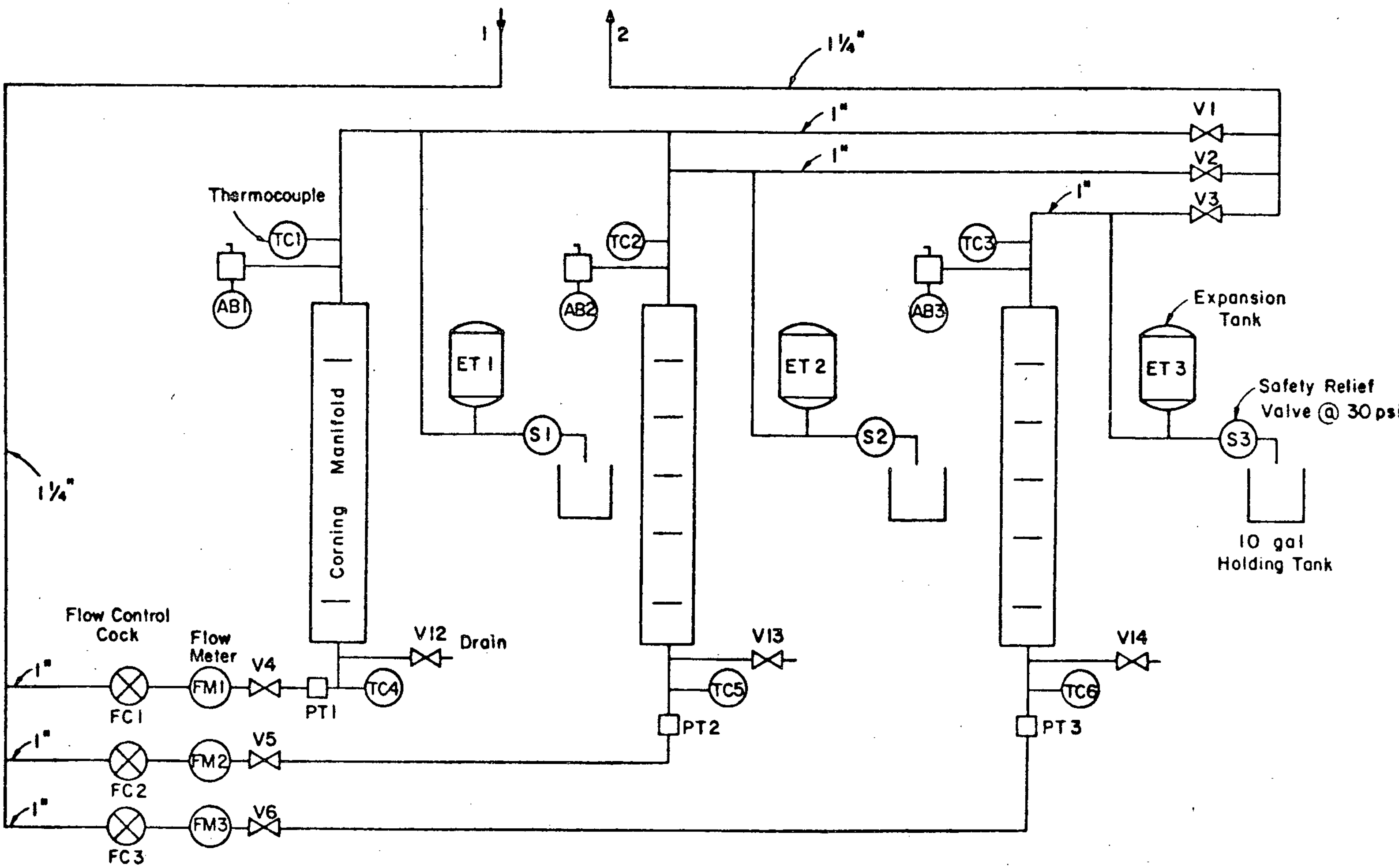


Figure 4. Solar House I: Collector Test Bed - Flow Diagram December 16, 1976

Table 2

Component List and Specifications

Code	Quantity	Item	Size-Make-Model	Photo #
AB 1-3	3	Air bleed	Taco 1/2" Model 417	2
TC 1-9	9	Thermocouples	Thermo Electric 5T-0120L	2
S 1-3	3	Safety relief valves	1" Watts No. 330 (30 psi)	3
V 1-6	6	Isolation valves	1" gate valves	4
FC 1-3	3	Flow meters	1/2" Cox Series 21	4
---	1	Air scoop	1-1/4" Taco Model 432	8
AB-4	1	Float bleed	1/2" American No. 400	8
V 7-8	2	Drain and fill connections	1" gate valves	9
FM-4	1	Flow meter	3/4" Cox Series 21	9
V 9-10	2	Pump insolation valves	1-1/2" gate valves	9
PI	1	Pressure indicator	1/2" Danton (0-60 psc)	9
P-11	1	Collector pump	Bell and Gosset (16 gpm @ 80 ft, 1-1/2 HP)	10
HX 11 & 12	2	Heat exchangers	Young Radiator Co., #F603 DY-1 pass	11
P-12	1	Storage pump	Bell and Gossett B-1&1/2 (25 gpm @ 7 ft, 1/6 HP)	11
HX 13	1	DHW heat exchanger	Young Radiator Co., #F303 HY-1 pass	12
---	1	Filter	1-1/4" Filtros Model CA-3	13
V-11	1	Filter insolation valve	1-1/4" gate valves	13
V-12-14	3	Drain valves	1/2" gate valves	14
PT 1-6	6	PT taps	1/2 Peterson	14
MV 1-6	6	3-way valves	1" Taco Model 557	17
---	1	Heat rejector	Trane 230-S	--
P-13	1	Heat rejector pump	Bell and Gossett (11 gpm @ 24 ft, 1/3 HP)	--
Tank #2	1	Storage tank	American Steel & Iron (11,000 gal)	--
FM-51	1	Heat rejector flow meter	1/2" Cox Series 21	--

the cooling load demands of the Solar House. Calculations by the University of Wisconsin showed that this performance should be obtainable with a gross collector area of 71.4 square meters (768 sq ft) facing the south (i.e., the angle, θ, between the projection of the sun's rays, at solar noon, on the horizontal plane and the projection of the normal to the collector on the horizontal plane is zero) at an inclination of 45 degrees (i.e., the angle between horizontal and normal to the collector), when combined with a heat storage of 4275 liters (1131 U.S. gallons) of water.

The Corning system has the same volume of heat storage and also faces due south at an inclination of 45 degrees. While the gross area of the collectors is basically the same (89 square meters test bed area minus area of manifolds and unused area) at 70 square meters (754 sq ft), the actual absorber area of 39.9 square meters (430 sq ft) is significantly reduced.

1.2.2.2 Control System Description -- CSU Solar House I utilizes a fully automatic on/off control system for the operation of the solar heating and cooling system. Extraction of heat from the solar collectors and distribution of heat to the heating, cooling, and hot water loads are automatically controlled in response to preset temperatures or temperature differentials. This is accomplished by feedback control loops consisting of sensors, thermostats, controlled elements and the mechanical system itself. Figure 5 illustrates a typical feedback control loop. The control sensors are vapor expansion bulb and capillary aquastats for the liquid temperatures and a conventional residential coil thermostat for air temperature in the house. The sensors for the temperature difference between the collector absorber

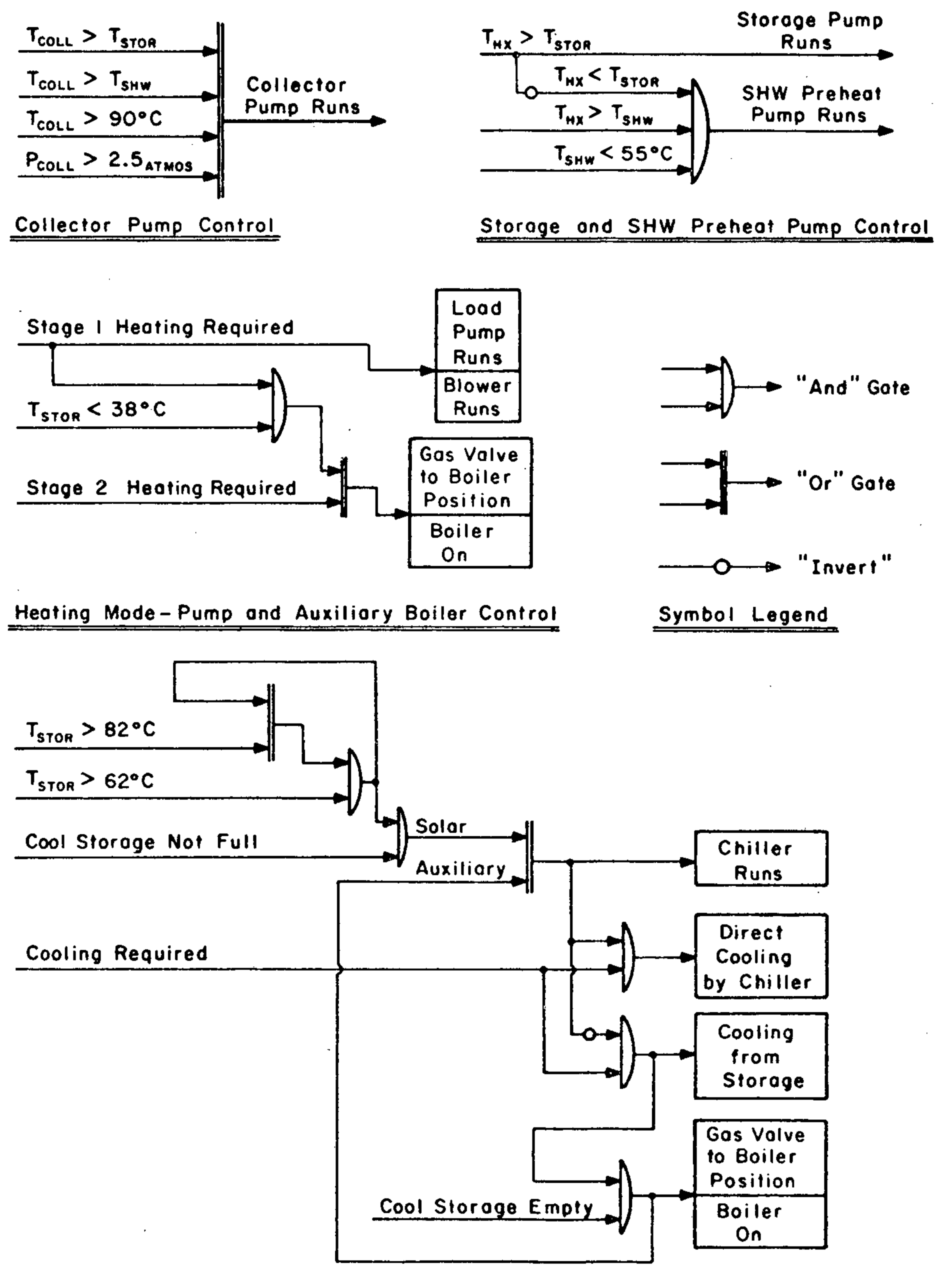


Figure 5. Cooling Mode - Chiller, Cool Storage and Auxiliary Control

plate and the storage tank bottom are electrical resistance elements (thermistors) for the flat-plate system and thermocouples for the evacuated tube system.

Thermostats are used to compare the sensor outputs with the correponding temperature or differential temperature settings. When the sensor output is sufficiently different from the setting (or is outside of the deadband), a control signal is transmitted from the thermostat to a power relay. The relay opens or closes the 110 volt power line to a controlled element which is a pump, motor, or an automatic valve positioner, or an air fan motor.

The mechanical system is the final link in the feedback control loop. It is affected by controlled elements which regulate flow to the various components. Operation of the solar air heating coil, for example, depends on the conditions of the main system pump (P1) and the heating/cooling automatic valve (VI) [Refer to Figures 1 and 2)]. The mechanical system produces an output measured as temperature by the control sensor, thus completing the feedback control loop. Through operation of the air coil, for example, house air temperature change is sensed by the wall thermostat. All control action is of the on/off type with adjustable set points and deadbands. Figure 5 is a simplified logic diagram of the control circuit.

The heat transfer system is characterized by the use of a heat exchanger which separates the collector fluid from the storage tank fluid. The collector fluid is pumped through the shell side of a commercially available shell and tube heat exchanger, while storage fluid is pumped through the tubes by another pump. Two main advantages of this configuration are the avoidance of antifreeze in the storage system and the use of non-pressurized (vented to the atmosphere) storage tank. Provision of the heat exchanger permits use of only 57 liters (15 gallons) of antifreeze in the collector loop. The storage tank then needs only water and a corrosion inhibiting additive. The second advantage of this configuration is a pressurized collector circuit and a non-pressurized storage tank, with the heat exchanger acting as the pressure barrier. There are two reasons for preferring a pressurized collector loop. Under pressure, the boiling temperature of the collector fluid is elevated, allowing for higher operating temperatures in the collector. With the heat exchanger preventing pressure in the storage tank, the collector loop can be completely fluid filled. Consequently, there is no gravity head loss for the pump to overcome, only frictional head loss.

The third advantage of this configuration concerns corrosion protection of the collector absorber plates. The need for continuous filtration and deionization of the collector fluid is a major consideration. Only the 106 liters (28 gallons) required to fill the collector loop receives such treatment and not the additional 4275 liters (1130 gallons) of fluid in storage.

Because of the high stagnation temperature (over 500°C) attainable by the evacuated tubular collector and the potential hazards associated with high temperature excursions, redundant controls were provided for the collector circulation pump. Primary control is provided by two differential thermostats that compare the temperature in storage with the temperature of the fluid in the collector. The collector pump is energized when the collector fluid is 10 degrees Celsius above the temperature at the bottom of either the main storage tank or the domestic hot water preheat tank and remains energized until the difference is less than two degrees Celsius. The collector pump is also energized when the collector loop pressure exceeds 2.5 atmospheres (22 psig) or the collector fluid temperature exceeds 90°C (194°F).

During initial start-up each day, only the fluid within the collectors has been heated; the remaining fluid in the loop is considerably cooler. Therefore the pump on the storage side of the heat exchanger is not activated until a differential temperature set point directly ahead of the heat exchanger is satisfied.

The service hot water preheat pump is energized when the temperature at the inlet to the heat exchanger is 10 degrees Celsius higher than that in the preheat tank. This mode will continue until the preheat temperature exceeds 55°C (131°F) or until the temperature at the inlet to the heat exchanger is high enough to add energy to the main storage tank.

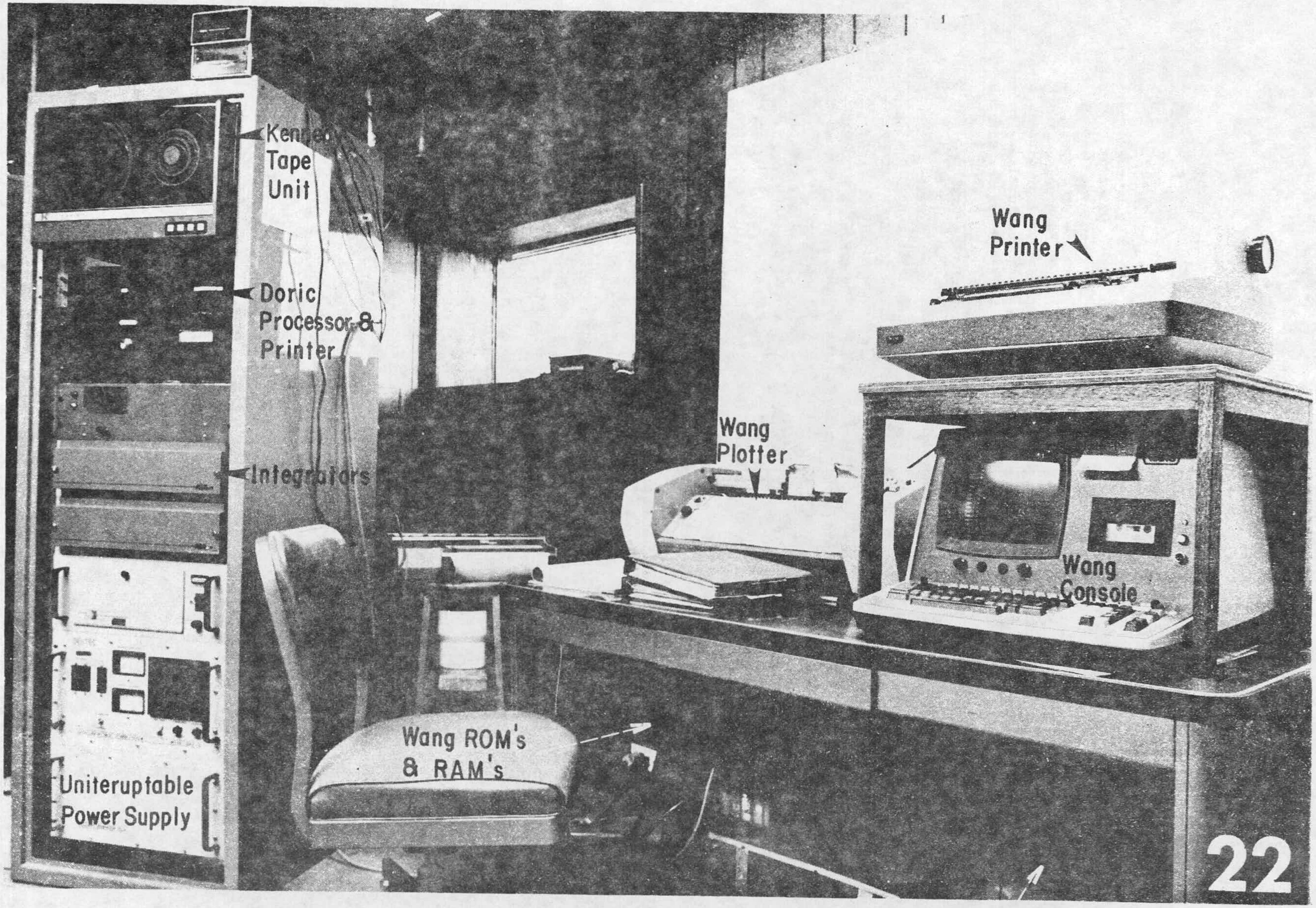
In the heating mode, the wall thermostat has two stages. In Stage 1, house heating is provided from solar storage provided the temperature at the top of the tank is greater than 38°C. If the storage temperature is below 38°C (100°F) or if Stage 2 heating is required, Valve V2 is activated and heating is provided solely by auxiliary.

Control in the cooling mode is slightly more complex because of cold storage and the operating characteristics of the Arkla chiller. The maximum cooling output and coefficient of performance occur when the water to the generator is about 80°C (176°F) and the chiller can operate effectively down to 66°C (150°F). However, the chiller is not allowed to operate from the solar storage until the temperature reaches 82°C (180°F) because it will operate below capacity and slow the temperature increase of the tank. The chiller is then allowed to operate from solar storage until the temperature drops below 66°C (150°F). If cooling is not demanded by the house thermostat, the chilled water is sent to cool storage. If cool storage is full, the chiller is shut down.

When the house thermostat calls for cooling, it is provided directly by the chiller. If the chiller is not operating, the load is met from cold storage. If the solar storage temperature is not sufficient to operate the chiller and chilled water is not available in cool storage, then the chiller is operated from the auxiliary boiler.

1.2.2.3. Instrumentation System - The Solar House I data acquisition system is shown in Photograph 3. The Doric data logger scans 80 channels (100 channels available) of analog signals once every ten minutes, converts to digital form, and linearizes the temperature signals and converts them to degrees Celsius. The data collected are listed in Table 3. These data are stored on the Kennedy 7-track magnetic tape and they are also processed by the Wang mini-computer and a summary of the system performance is printed each hour. Component malfunction and instrument error flags are also printed. At the end of the day (6:02 am), a daily performance summary is printed. Hourly system performance items and daily summary items are listed in Table 4. A complete set of hourly average values of each of the data items in Table 4 are also printed at this time.

The arrangement of and interactions between various components of the Wang system are shown in Figure 6. Component specifications are given in Table 5.



Photograph 3. Solar House I Data Acquisition and Analysis System

Table 3

Data Collected

Acronym	Description	Acronym	Description
TBFP	Temperature behind flat plate collector	TWT	Temperature of warm storage tank
TRTFP	Tank room temperature (flat plate)	TCT	Temperature of cool storage tank
TUSTFP	Temperature under flat plate storage tank	TFAC	Temperature from alternate coil
TTCFPB	Basement temperature to flat plate collector	TTAC	Temperature to alternate coil
TTCFPA	Attic temperature to flat plate collector	TRA	Temperature of return air
TFCFPB	Basement temperature from flat plate collector	TSA	Temperature of supply air
TFCFPA	Attic temperature from flat plate collector	TFCT	Temperature from cooling tower
STBFP	Bottom flat plate storage tank temperature	TTCT	Temperature to cooling tower
STMFP	Middle flat plate storage tank temperature	TSHW	Service hot water temperature
STTFP	Top flat plate storage tank temperature	TP	Temperature of preheat tank
TFHR	Temperature from heat rejector	THW	House dew point temperature
TTHR	Temperature to heat rejector	THD	House air temperature
TTM3	Temperature to Module 3 (west)	TOD	Outdoor air temperature
TTM2	Temperature to Module 2 (middle)	SYST	Collector supply house load
TTM1	Temperature to Module 1 (east)	M2IND	Mode 2 Indicator
TFM3	Temperature from Module 3	V2IND	Solar/Auxiliary Indicator
TFM2	Temperature from Module 2	V3IND	Normal/Alternate Mode Indicator
TFM1	Temperature from Module 1	P7IND	Pump 7 on/off indicator
TBTB	Temperature behind test bed	P6IND	Pump 6 on/off indicator
TTA1	Temperature to Array 1	IP3OT	P3 on time
TTA2	Temperature to Array 2	IWIND	Wind run (integrated)
TTA3	Temperature to Array 3	IFAC	Integrated alternative coil flow rate
TFA1	Temperature from Array 1	IFCT	Integrated flow of cooling tower
TFA2	Temperature from Array 2	IFCH	Integrated flow of chiller
TFA3	Temperature from Array 3	IFPEL	Integrated flat plate electric
TRT	Tank room temperature	IP1EL	Load pump (P1) integrated electricity
TUST	Temperature under storage tank	ISEL	Integrated solar electric power
TTC	Basement temperature to test bed collector	IHWGAS	Integrated hot water gas consumption
TFC	Basement temperature from test bed collector	IBGAS	Integrated boiler gas consumption
STB	Storage tank bottom temperature	IFHW	Integrated hot water flow
STM	Storage tank middle temperature	IFHR	Integrated heat rejector flow
STT	Storage tank top temperature	IFL	Integrated load flow rate
TFL	Temperature from load	IFCFP	Integrated flat plate collector flow
TTL	Temperature to load	IFA3	Integrated flow - Array 3
TTCHG	Temperature to chiller generator	IFA2	Integrated flow - Array 2
		IFA1	Integrated flow - Array 1
		IFC	Integrated collector - flow rate
		ISS	Integrated solar spectral radiation
		ISHO	Integrated horizontal insolation
		IS45	Test bed integrated 45° insolation
		IS45FP	Flat plate integrated 45° insolation

Table 4

Items Calculated from the Scanned Data

Acronym	Description	Acronym	Description
CDEGDA	Cooling degree days	QBG	Total heat content of the gas burned in the boiler
CLDDD	Cooling load calculated from degree day data	QCOOL	Actual cooling accomplished
CLDM	Changed to QAIR	QCOOLS	Cooling actually accomplished by solar
COP	Coefficient of performance of the LiBr chiller	QCTR	Energy removed by the cooling tower
COT	Collector on time in seconds. It is calculated from the collector flow assuming an average mass flow rate	QHCG	Heat delivered to the primary and alternate coil by gas
		QHWG	Total heat content of gas burned to heat the service hot water tank
DELQST	Change in energy in storage during the day	QLOAD	Heating or cooling energy actually supplied to the house (does not include inadvertent energy supplied via storage)
EFFO	Collector efficiency while collector is on		
EFFT	Collector efficiency for entire day	QPCS	Heat energy delivered to the primary coil by solar
ELECS	Electricity used to run solar equipment	QSHB	Total solar supplied energy as calculated from an energy balance
HDEGDA	Heating degree days	QSHWS	Energy supplied to the preheat tank by solar
HLDDD	Heating load calculated from degree day data	QSOLAR	Summation of measured solar energy supplied
HLDM	Heating load measured		
HOURFR	Fraction of time which collector is operating	QSTOR	Energy available in storage above 20°C
HOURO	Hours of operation for collector during the day	QU	Useful energy gain from collectors
		S45	Integrated insolation at 45°
HWGAL	Hot water usage in liters	S450	Integrated insolation at 45° while collector is on
MCLD	Measured cooling load		
PCTARCS	Percent of energy delivered to the chiller which is solar supplied	SOLCOL	Percent of actual cooling accomplished by solar
		TODO	Outdoor temperature while collector is on
PCTHTS	Percent of heating energy which is solar supplied	TSTOR	Average storage tank temperature (STT + STM + STB)/3
PCTSHWS	Percent of energy to service hot water which is solar supplied	TSTORO	Average storage tank temperature while the collector is on
QAIR	(Solar + gas) Energy to the chiller (formerly CLDM)	WIND	Average wind speed in kilometers/hour
QAIRCG	Gas supplied energy to the chiller		
QAIRCS	Solar supplied energy to the collector	WINDO	Average wind speed while collector is operating
QAUX	Auxiliary energy supplied for either heating or cooling, but not service hot water	XLOAD	Energy to either heating or cooling load (similar to QLOAD)
		QHR	Energy to simulated load

Temperatures in degrees Celsius
Gas flows are in cubic meters
Other flows are in liters
Energy units are Megajoules

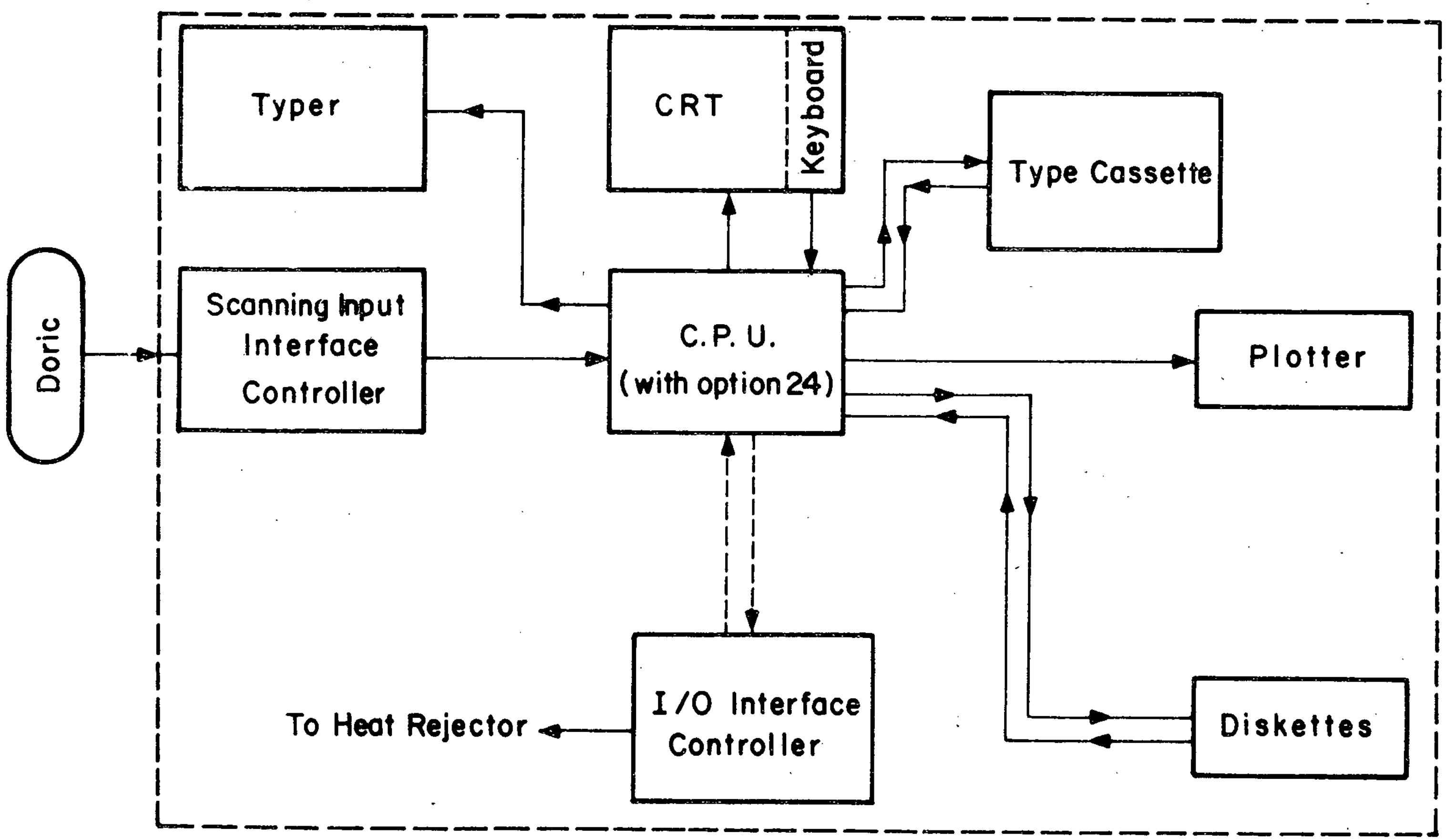


Figure 6. Wang System Configuration

Table 5

Component Specifications

†CPU	†TAPE CASSETTE
Wang model 2200S ** 32K byte memory (expanded from 4K bytes) Read/write cycle time 1.6 μsec Average execution times: Add/subtract Multiply divide 3.87/7.4 msec ln X/X^y 23.2/45.4 msec cos/tan 38.9/78.5 msec	Capacity 78K bytes 522 bytes/foot Recording and search speed 7.5 IPS Transfer rate 326 characters/second Stop/start time .09/.05 seconds Inter-record gap .6 inch Model 2217
**DISKETTES:	†PLOTTER
2 diskettes, 262144 bytes/diskette 524288 total bytes 256 bytes/sector 1024 sectors/diskette Rotation speed 360 rpm Access time: Min = 14 msec Avg = 363 msec Max = 726 msec Average latency time 83.3 msec Read/write time per sector 21.8 msec Raw transfer rate 30 K bytes/sec Move/copy time 2 min (approx) Model 2270-2	Plot width 6" (any length) Paper: fan-fold sprocket-feed 17" wide Plotting increment .005 inch Plotting accuracy .01 inch plus .1 %/inch Plotting speed 3 inch/sec Single pen Buffer: 40 bytes Alphanumeric plotting 64 ASCII characters 15 selectable sizes Model 2272-1
**SCANNING INPUT INTERFACE CONTROLLER	*I/O INTERFACE CONTROLLER
1 to 10 BCD digits with sign bit 100 readings/second Parallel transfer format Signal levels 0 → 4V = 0 2.5 → 5V = 1 Model 2252A	I/O circuitry TTL/DTL compatible Voltage levels +2.4 → 3.6V = 0 0 → +.4 = 1 Data transfer - sequential transfer of 8 bit parallel information, under program control Model 2250
†CRT KEYBOARD	†TYPER
Display size 8" x 10.5" 16 lines with 64 characters/line Character size = .20" x .12" Model 2216A	156 characters wide, 12 characters/second Model 2201
	**OPTION 24
	Option 24 was added to the CPU to implement the plotter and the disk

* Purchased on Project E(11-1)-4012
** Purchased on Project E(11-1)-2577
† Provided by Colorado State University

Table 6 lists the specifications of instrumentation purchased as part of the project being reported. Additional new instrumentation has been purchased on the continuing Solar House I project.

Table 6

Purchased Instrumentation Specifications

AGM INTEGRATOR MODULES AND RACK MOUNT

4 each Model EA 4011-3 Resettable Integrators
- 1 each - 0-15 mV d.c. input
  10 minute integration
  250 mV d.c. maximum output for pyranometer
- 3 each = 0.55 mV d.c. input
  10 minute integration
  250 mV d.c. maximum output for watt transducers

7 each Model EA 4050 Pulse Accumulators
- 4 each - 0-800 Hz, 10-500 mV peak to peak input
  10 minute accumulation
  250 mV d.c. maximum output for turbine flowmeters
- 3 each - 0-1 Hz TTL pulse input
  10 minute accumulation
  250 mV d.c. maximum output for Monsanto 8 photodetector counting gas and water meter revolution

Accuracy:	± 0.25% full scale
Operating temp:	0 - 50°C
Power:	24V d.c. ± 10%
Reset:	TTL pulse

24 volt d.c. power supply for above

Input:	115V a.c. ± 10%
Output:	24V d.c. ± 0.1%, 8 amp maximum

COX TURBINE FLOWMETERS

4 each Model 3/4-30 Series 21

Fluid connections:	3/4 inch NPT
Flow range:	3-30 gpm
Repeatability:	0.1% from 100-1000 Hz
Accuracy:	0.5% full scale including linearity
Pressure rating:	1500 psig at 100°F
Temperature range:	-30°F to 400°F
Output:	minimum 10 mV at 100 Hz
Bearings:	carbide sleeve
Electric connections:	magnetic pickoff
Construction:	stainless steel

4 each Model 1/2-15 Series 21

Fluid connections:	1/2 inch NPT
Fluid range:	1.5 to 15 gpm
Repeatability:	0.1% from 100-1000 Hz
Accuracy:	0.5% full scale including linearity
Pressure rating:	1500 psig at 100°F
Temperature range:	-30°F to 400°F
Output:	minimum 10 mV at 100 Hz
Bearings:	carbide sleeve
Electric connections:	magnetic pickoff
Construction:	stainless steel

F.W. BELL WATT TRANSDUCERS

4 each Model PX-2202B

Rated current and power levels:

Single phase series coils:	10.0A, 1000W
Single phase shunt coils:	20.0A, 2000W
Voltage:	0 - 135 volts
Frequency:	60 Hz ± 20%
Output:	± 55 mV d.c. ± 1% across 50Ω
Source resistance:	≤ 20Ω
Linearity vs power:	≤ 0.2%
Temperature:	20-30°C
Accuracy:	0.5%

EPPLEY PYRANOMETER

1 each Model PSP Precision Spectral Pyranometer

Sensitivity:	11 microvolts/watt meter^{-2} nominal
Impedance:	650 ohms nominal
Temperature dependence:	± 1% from -20° to +40°C
Linearity:	± 0.5% from 0 to 2800 watts per square meter
Response time:	1 second (1/e signal)
Cosine response:	± 1% from normalization 0 - 70° zenith angle ± 3% 70-80° zenith angle

THERMOELECTRIC THERMOCOUPLES

15 each, Model 5T-0120L, type T, 6 inch Sheathed thermocouples with plug, jack, and compression fitting

Measuring junction:	Welded, grounded type
Calibration:	ISA-T (Copper-Constantan)
Sheath material:	300 stainless steel
Sheath diameter:	1/8 inch
Connectors:	Polarized ISA color coded plugs and jacks with thermocouple material contacts
Temperature range:	-200 to +400°C

2. System Thermal Performance

2.1 Daily, Monthly, and Annual Values of Mean Daily Heat Flows

2.1.1. Total Energy Required

Tables 7 through 15 show the daily values of the total energy required for space heating and cooling, domestic hot water heating, and the combined total energy required. Included in the tables are daily values of solar energy used, auxiliary energy used, and the fraction of the load provided by solar energy in each of the same four categories. Collector performance is indicated in the tables by daily values of total solar radiation incident on the collector absorber plates, the solar radiation incident while the collectors were running, the heat delivered to the system from the collectors, and the average efficiency defined as the fraction of the total solar radiation collected. The last column of the table is the estimated quantity of heat lost from the main solar energy storage tank which acts to heat the building. It was completed by use of data on storage water temperature and a heat loss coefficient.

Days for which no data are available are left blank in the tables. No data is available for May, June, and July due to mechanical failure and repairs to the Doric data scanner. The totals for each category, the daily mean, and a monthly total based on extrapolation of the daily means are included at the bottom of each table.

The data presented were obtained during the period 1 October 1976 to 30 September 1977. It should be noted that all data prior to 1 January 1977 pertain to the flat-plate collector system with 67.0 square meters of absorber area and all data after 1 January 1977 pertain to the

Table 7. CSU Solar House I: System Performance for Month of October, 1976

	SPACE HEATING, SPACE COOLING, AND DOMESTIC WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collecting	Heat Delivered	Average Efficiency	Heat Lost to Conditioned Space
1	0.0	413.4	223.5	636.9	0.0	317.3	47.4	364.7	0.0	96.1	176.1	272.2	--	.762	.212	.573	1,960.9	1,470.6	452.2	.221	54.9
2	0.0	287.8	351.7	639.5	0.0	88.7	51.7	140.4	0.0	199.1	300.0	499.1	--	.308	.147	.220	1,404.9	942.6	185.6	.132	51.4
3	0.0	196.8	250.0	446.8	0.0	0.0	47.3	47.3	0.0	196.8	202.7	399.5	--	0.0	.189	.106	1,169.2	584.6	122.8	.105	51.9
4	0.0	127.2	315.3	442.5	0.0	0.0	48.3	48.3	0.0	127.2	267.0	394.2	--	0.0	.153	.109	1,035.2	459.4	95.0	.092	53.5
5	4.9	357.8	213.7	576.4	0.0	0.0	45.9	45.9	4.9	357.8	167.8	530.5	0.000	0.0	.215	.080	1,205.1	644.3	131.8	.109	54.5
6	0.0	155.6	245.1	400.7	0.0	0.0	45.3	45.3	0.0	155.6	199.8	355.4	--	0.0	.185	.113	939.6	590.6	116.2	.124	57.7
7	0.0	0.0	285.1	285.1	0.0	0.0	45.0	45.0	0.0	0.0	240.1	240.1	--	0.0	.158	.158	1,840.5	1,428.8	300.8	.163	67.9
8	0.0	441.6	276.5	718.1	0.0	441.6	49.2	490.8	0.0	0.0	227.3	227.3	--	1.000	.178	.178	1,918.0	1,324.4	285.6	.149	71.7
9	0.0	489.5	366.3	855.8	0.0	345.0	72.1	417.0	0.0	144.5	294.2	438.7	--	.705	.197	.487	1,822.6	1,658.9	451.7	.247	55.6
10	0.0	560.1	332.0	892.1	0.0	332.5	46.5	379.0	0.0	227.6	285.5	513.1	--	.594	.140	.425	1,801.7	1,688.3	430.3	.238	55.0
11	0.0	220.4	363.1	583.5	0.0	0.0	14.5	14.5	0.0	220.4	348.6	569.0	--	0.0	.040	.024	331.1	47.7	9.5	.029	48.8
12	0.0	0.0	327.1	327.1	0.0	0.0	48.9	48.9	0.0	0.0	278.2	278.2	--	0.0	.150	.149	1,393.0	1,142.5	268.1	.192	58.7
13	0.0	253.4	312.0	565.4	0.0	222.9	49.4	272.3	0.0	30.5	262.6	293.1	--	.880	.158	.482	1,712.2	1,306.5	296.9	.173	69.6
14	0.0	280.2	237.9	518.1	0.0	241.4	48.3	289.7	0.0	38.8	189.6	228.4	--	.861	.203	.559	1,655.5	1,378.1	342.2	.206	64.3
15																					
16	37.1	0.0	77.4	114.5	37.1	0.0	49.9	87.0	0.0	0.0	27.5	27.5	1.0	0.0	.645	.760	1,676.4	1,300.5	269.6	.161	76.2
17	27.8	0.0	65.9	93.7	27.8	0.0	54.0	81.8	0.0	0.0	11.9	11.9	1.0	0.0	.819	.873	1,261.8	1,079.8	77.2	.061	76.4
18	0.0	0.0	85.1	85.1	0.0	0.0	49.4	49.4	0.0	0.0	35.7	35.7	--	0.0	.581	.580	1,061.9	250.6	37.0	.035	69.4
19	0.0	0.0	81.5	81.5	0.0	0.0	8.9	8.9	0.0	0.0	72.6	72.6	--	0.0	.109	.109	1,703.2	0.0	0.0	0.0	64.0
20																					
21	0.0	0.0	124.5	124.5	0.0	0.0	47.4	47.4	0.0	0.0	77.1	77.1	--	0.0	.381	.381	1,655.5	155.1	42.0	.025	55.3
22	0.0	0.0	143.4	143.4	0.0	0.0	30.7	30.7	0.0	0.0	112.7	112.7	--	0.0	.214	.214	1,425.8	453.4	146.1	.102	55.3
23	0.0	0.0	89.8	89.8	0.0	0.0	50.3	50.3	0.0	0.0	39.5	39.5	--	0.0	.560	.560	1,488.5	1,387.1	239.7	.161	64.8
24	0.0	0.0	112.0	112.0	0.0	0.0	53.2	53.2	0.0	0.0	58.8	58.8	--	0.0	.475	.475	1,336.3	1,291.6	84.4	.063	68.5
25	0.0	0.0	94.9	94.9	0.0	0.0	54.3	54.3	0.0	0.0	40.6	40.6	--	0.0	.577	.572	1,249.8	918.7	202.0	.161	65.9
26	0.0	0.0	4.4	4.4	0.0	0.0	4.4	4.4	0.0	0.0	0.0	0.0	--	0.0	1.0	1.0	119.3	0.0	0.0	0.000	63.1
27	0.0	0.0	56.4	56.4	0.0	0.0	55.5	55.5	0.0	0.0	.9	.9	--	0.0	.984	.984	1,020.1	548.9	114.8	.112	57.2
28																					
29	0.0	0.0	172.1	172.1	0.0	0.0	115.5	115.5	0.0	0.0	55.6	56.6	--	0.0	.672	.671	2,180.5	1,897.1	491.7	.224	74.7
30	0.0	0.0	90.4	90.4	0.0	0.0	45.2	45.2	0.0	0.0	45.2	45.2	--	0.0	.500	.500	1,181.2	951.5	23.6	.020	74.5
31	0.0	0.0	99.2	99.2	0.0	0.0	44.3	44.3	0.0	0.0	54.9	54.9	--	0.0	.446	.447	1,771.8	1,622.7	169.6	.096	72.2
Total	70.0	3,874.0	5,396.0	9,250.0	65.0	1,989.0	1,323.0	3,377.0	5.0	1,794.0	4,074.0	5,873.0	.929	.474	.245	.365	39,321.0	26,524.0	5,359.0	.136	1,753.0
Mean	2.5	135.1	192.7	330.3	2.3	71.1	47.2	120.6	0.2	64.1	145.5	209.8	.929	.474	.245	.365	1,404.3	947.3	191.4	.136	62.6
Month	77.0	4,189.0	5,974.0*	10,240.0	72.0	2,203.0	1,465.0	3,739.0	6.0	1,987.0	4,510.0	6,502.0	.929	.474	.245	.365	43,534.0	29,366.0	5,934.0	.136	1,940.6

[1] All data in megajoules

[2] Performance based on 71.3 m^2 flat plate absorber area.

*Excluding contribution to space heating by heat losses from main solar storage and from DHW preheat tank.

Table 8. CSU Solar House I: System Performance for Month of November, 1976

	SPACE HEATING, SPACE COOLING, AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collecting	Heat Delivered	Average Efficiency	Heat Lost to Conditioned Space
1	0.0	0.0	133.4	133.4	0.0	0.0	68.4	68.4	0.0	0.0	65.0	65.0	--	--	.513	.513	1,855.3	1,082.8	250.7	.135	75.8
2																					
3																					
4	29.0	86.7	244.9	360.6	29.0	86.7	65.3	181.0	0.0	0.0	179.6	179.6	1.0	1.000	.267	.502	1,822.6	1,246.9	254.4	.134	71.4
5	0.0	0.0	264.4	264.4	0.0	0.0	186.2	186.2	0.0	0.0	78.2	78.2	--	--	.704	.704	1,837.5	1,118.6	232.9	.127	71.4
6	0.0	0.0	138.5	138.5	0.0	0.0	45.8	45.8	0.0	0.0	92.7	92.7	--	--	.331	.331	969.4	429.5	82.6	.085	73.7
7	0.0	0.0	197.7	197.7	0.0	0.0	60.6	60.6	0.0	0.0	137.1	137.1	--	--	.306	.307	1,548.1	238.6	45.7	.029	68.0
8	8.5	0.0	144.7	153.2	8.5	0.0	5.2	13.7	0.0	0.0	139.5	139.5	1.0	--	.306	.089	1,634.6	0.0	0.0	0.000	61.1
9																					
10																					
11	176.6	0.0	170.7	347.3	176.6	0.0	31.0	207.6	0.0	0.0	139.7	139.7	1.0	--	.182	.598	155.1	0.0	0.0	0.000	41.7
12	340.6	0.0	155.1	495.7	280.3	0.0	6.1	286.4	60.3	0.0	149.0	209.3	1.0	--	.039	.578	158.1	3.0	0.0	0.000	11.6
13	60.9	0.0	105.0	165.9	0.0	0.0	6.6	6.6	60.9	0.0	98.4	159.3	0.0	--	.063	.040	295.3	0.0	0.0	0.000	0.0
14	243.3	0.0	219.6	462.9	81.5	0.0	34.7	116.2	161.8	0.0	184.9	346.7	.335	--	.158	.251	865.0	760.6	212.5	.245	2.5
15	89.7	0.0	216.9	306.6	0.0	0.0	45.7	45.7	89.7	0.0	171.2	260.9	0.0	--	.211	.149	1,637.6	1,506.4	536.0	.327	21.5
16	39.5	0.0	156.4	195.9	39.5	0.0	54.3	93.8	0.0	0.0	102.1	102.1	1.0	--	.347	.479	1,518.3	1,237.9	353.9	.233	43.0
17	0.0	0.0	141.4	141.4	0.0	0.0	43.8	43.8	0.0	0.0	97.6	97.6	--	--	.310	.310	1,634.6	1,404.9	443.6	.271	47.1
18	0.0	0.0	114.7	114.7	0.0	0.0	43.4	43.4	0.0	0.0	71.3	71.3	--	--	.378	.378	539.9	256.5	106.3	.196	42.8
19	0.0	0.0	144.1	144.1	0.0	0.0	52.0	52.0	0.0	0.0	92.1	92.1	--	--	.361	.361	1,413.9	1,202.1	376.3	.266	45.9
20	9.7	0.0	91.7	101.4	9.7	0.0	41.0	50.7	0.0	0.0	50.7	50.7	1.0	--	.447	.500	1,058.9	820.3	162.8	.153	41.5
21	112.8	0.0	205.8	318.6	112.8	0.0	29.0	141.8	0.0	0.0	176.8	176.8	1.0	--	.141	.445	1,479.5	1,416.9	372.2	.251	39.6
22	86.7	0.0	185.3	272.0	81.4	0.0	44.8	126.2	5.3	0.0	140.5	145.8	.939	--	.242	.464	337.1	101.4	25.0	.074	36.2
23	87.4	0.0	105.7	193.1	78.5	0.0	43.6	122.1	8.9	0.0	62.1	71.0	.898	--	.413	.632	1,139.5	814.3	253.0	.662	32.5
24																					
25	9.4	0.0	79.2	88.6	9.4	0.0	44.3	53.7	0.0	0.0	34.9	34.9	1.0	--	.559	.606	1,264.7	1,231.9	304.7	.241	44.6
26	533.7	0.0	102.0	635.7	533.7	0.0	36.0	569.7	0.0	0.0	66.0	66.0	1.0	--	.353	.896	486.2	298.3	36.0	.074	32.2
27	445.4	0.0	69.0	514.4	267.5	0.0	28.6	296.1	178.0	0.0	40.4	218.4	.600	--	.414	.576	1,154.4	1,023.1	307.3	.266	14.9
28	785.0	0.0	104.4	889.4	30.3	0.0	42.4	72.7	754.7	0.0	62.0	816.7	.039	--	.406	.082	856.1	528.0	106.1	.124	10.0
29	537.6	0.0	82.9	620.5	0.0	0.0	34.5	34.5	537.6	0.0	48.3	585.9	0.0	--	.417	.056	599.6	235.6	34.6	.058	11.9
30	383.7	0.0	68.4	452.1	97.6	0.0	40.5	138.1	286.1	0.0	27.9	314.0	.254	--	.593	.305	542.9	280.4	68.0	.125	11.8
31																					
Total	3,980.0	87.0	3,642.0	7,708.0	1,836.0	87.0	1,134.0	3,057.0	2,143.0	0.0	2,508.0	4,651.0	.461	1.000	.311	.397	23,284.0	17,238.0	4,556.0	.161	952.0
Mean	159.2	3.5	145.7	308.3	73.5	3.5	45.4	122.3	85.7	0.0	100.3	186.1	.461	1.000	.311	.397	1,131.3	689.5	182.2	.161	38.1
Month	4,775.0	104.0	4,370.0	9,450.0	2,204.0	104.0	1,361.0	3,668.0	2,572.0	0.0	3,010.0	5,582.0	.461	1.000	.311	.397	33,940.0	20,686.0	5,467.0	.161	1,143.0

[1] All data in megajoules

[2] Performance based on 71.3 m^2 flat plate absorber area

Table 9. CSU Solar House I: System Performance for Month of December, 1976

	SPACE AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collect-ing	Heat Deliv-ered	Average Effi ciency	Heat Lost to Condi-tioned Space
1	345.2	0.0	79.4	424.6	58.3	0.0	43.1	101.4	286.9	0.0	36.3	323.2	.169	--	.543	.239	999.3	763.6	226.3	.226	10.3
2	124.1	0.0	99.6	223.7	106.0	0.0	45.2	151.2	18.1	0.0	54.4	72.5	.854	--	.454	.676	1,208.1	1,049.9	429.5	.355	19.8
3	127.8	0.0	13.1	140.1	0.0	0.0	0.0	0.0	127.8	0.0	13.1	140.9	0.0	--	0.0	0.0	11.9	0.0	0.0	0.0	30.6
4	380.4	0.0	72.8	453.2	0.0	0.0	54.1	54.1	380.4	0.0	18.7	399.1	0.0	--	.743	.119	951.5	587.6	135.5	.142	40.1
5	404.6	0.0	101.5	506.1	0.0	0.0	50.2	50.2	404.6	0.0	51.3	455.9	0.0	--	.495	.099	1,008.2	885.9	195.8	.194	45.8
6	344.0	0.0	88.8	432.8	0.0	0.0	53.8	53.8	344.0	0.0	35.0	379.0	0.0	--	0.0	.124	1,515.3	987.3	226.2	.149	54.7
7	134.9	0.0	88.1	233.0	0.0	0.0	55.1	55.1	134.9	0.0	33.0	167.9	0.0	--	.625	.247	1,157.4	936.6	192.2	.166	60.7
8	233.4	0.0	253.6	487.0	4.8	0.0	179.1	183.9	228.6	0.0	74.5	303.1	.021	--	.706	.378	1,291.6	1,082.8	287.7	.223	60.3
9	154.3	0.0	283.5	437.8	54.5	0.0	139.0	193.5	99.9	0.0	144.5	244.4	.353	--	.490	.442	823.3	590.6	139.0	.169	51.1
10	119.5	0.0	59.4	178.9	118.0	0.0	23.7	141.7	1.5	0.0	35.7	37.2	.987	--	.399	.792	763.6	426.6	64.7	.085	32.5
11																					
12																					
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31																					
Total	2,368.0	0.0	1,140.0	3,508.0	342.0	0.0	643.0	985.0	2,027.0	0.0	497.0	2,523.0	.144	--	.564	.281	9,730.0	7,311.0	1,896.9	.195	40.6
Mean	236.8	0.0	114.0	350.8	34.2	0.0	64.3	98.5	202.7	0.0	49.7	252.3	.144	--	.564	.281	973.0	731.1	189.7	.195	40.6
Month	7,341.0	0.0	3,534.0	10,875.0	1,060.0	0.0	1,993.0	3,054.0	6,284.0	0.0	1,541.0	7,821.0	.144	--	.564	.281	30,164.0	22,664.0	5,880.0	.195	1,258.0

[1] All data in megajoules

[2] Performance based on 71.3 m^3 flat plate absorber area

Table 10. CSU Solar House I: System Performance for Month of January, 1977

	SPACE HEATING, SPACE COOLING AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collecting	Heat Delivered	Average Efficiency	Heat Lost to Conditioned Space
1																					
2																					
3	281.4	0.0	74.8	356.2	281.4	0.0	21.8	303.2	0.0	0.0	53.0	53.0	1.0	--	.292	.851	414.3	383.2	317.5	.766	27.7
4	509.9	0.0	77.5	587.4	293.5	0.0	21.1	314.6	216.5	0.0	56.4	272.9	.576	--	.273	.536	135.0	15.8	23.6	.175	14.1
5	661.7	0.0	241.4	902.8	174.5	0.0	35.2	209.7	487.1	0.0	206.2	693.3	.264	--	.146	.232	423.7	367.2	301.5	.711	11.1
6	485.3	0.0	142.9	628.2	211.3	0.0	18.6	229.9	274.0	0.0	124.3	398.3	.435	--	.130	.366	480.3	413.2	314.8	.656	12.7
7	203.3	0.0	143.9	347.2	203.3	0.0	29.0	232.3	0.0	0.0	114.9	114.9	1.0	--	.201	.669	722.1	697.1	629.8	.872	30.1
8	583.3	0.0	215.4	798.7	517.7	0.0	57.2	574.9	65.6	0.0	158.2	223.8	.888	--	.265	.720	262.1	143.1	58.0	.221	19.8
9	965.0	0.0	144.5	1,109.5	239.8	0.0	19.9	259.7	725.2	0.0	124.6	849.8	.249	--	.137	.234	879.6	767.9	450.6	.512	14.9
10																					
11																					
12	471.2	0.0	123.5	594.7	462.6	0.0	32.2	494.8	8.6	0.0	91.3	99.9	.982	--	.261	.832	184.3	49.8	38.5	.209	27.6
13	288.1	0.0	71.3	359.4	288.1	0.0	19.8	307.9	0.0	0.0	51.5	51.5	1.0	--	.278	.857	746.5	702.8	635.5	.851	27.1
14	256.6	0.0	72.3	328.9	250.0	0.0	32.8	282.8	6.7	0.0	39.5	46.2	.974	--	.454	.860	315.5	237.2	154.7	.490	41.1
15	499.6	0.0	70.5	570.1	499.6	0.0	29.6	529.2	0.0	0.0	40.9	40.9	1.0	--	.420	.928	244.6	57.4	59.1	.242	25.2
16	586.1	0.0	124.2	710.3	185.0	0.0	25.2	210.2	401.1	0.0	99.0	500.1	.316	--	.203	.296	623.1	568.6	526.9	.846	16.2
17	328.6	0.0	56.3	384.9	309.4	0.0	15.1	324.5	19.3	0.0	41.2	60.5	.941	--	.269	.843	633.6	588.2	581.2	.917	27.3
18	260.3	0.0	84.5	344.8	260.3	0.0	38.3	298.6	0.0	0.0	46.2	46.2	1.0	--	.454	.866	264.3	165.0	93.0	.352	21.7
19	389.1	0.0	104.2	493.3	346.5	0.0	67.4	413.9	42.6	0.0	36.8	79.4	.890	--	.647	.839	789.9	746.1	618.5	.783	33.0
20	484.2	0.0	122.6	606.8	484.2	0.0	59.3	543.6	0.0	0.0	63.3	63.3	1.0	--	.484	.896	830.9	805.9	663.4	.798	46.5
21	305.6	0.0	145.7	451.3	305.6	0.0	39.4	345.1	0.0	0.0	106.3	106.3	1.0	--	.271	.765	533.9	487.9	368.5	.690	52.8
22																					
23	612.1	0.0	151.1	763.2	612.1	0.0	64.8	676.9	0.0	0.0	86.3	86.3	1.0	--	.429	.887	718.9	700.0	593.3	.825	40.7
24	555.6	0.0	129.9	685.5	555.6	0.0	59.0	614.6	0.0	0.0	70.9	70.9	1.0	--	.454	.897	804.6	769.9	640.8	.796	45.3
25	369.6	0.0	176.5	546.1	369.6	0.0	96.9	466.6	0.0	0.0	79.6	79.6	1.0	--	.549	.922	909.5	889.8	680.3	.748	55.3
26	521.3	0.0	106.9	628.2	521.3	0.0	28.3	549.6	0.0	0.0	78.6	78.6	1.0	--	.265	.875	551.1	471.9	274.0	.559	59.9
27	323.9	0.0	153.5	477.4	323.9	0.0	37.4	361.3	0.0	0.0	116.1	116.1	1.0	--	.244	.757	920.2	870.6	679.3	.738	63.9
28	917.9	0.0	96.6	1,014.5	917.9	0.0	31.4	949.3	0.0	0.0	65.2	65.2	1.0	--	.325	.937	889.9	862.1	587.5	.661	66.9
29	720.9	0.0	92.3	813.2	720.9	0.0	63.0	783.9	0.0	0.0	29.3	29.3	1.0	--	.682	.964	800.7	655.2	399.3	.499	54.8
30	571.0	0.0	119.6	690.6	571.0	0.0	47.8	618.8	0.0	0.0	71.8	71.8	1.0	--	.400	.896	872.5	827.1	655.3	.751	50.4
31	262.8	0.0	107.4	370.2	262.8	0.0	37.2	300.0	0.0	0.0	70.2	70.2	1.0	--	.346	.810	868.8	838.7	602.2	.693	63.2
Total	12,414.0	0.0	3,149.0	15,564.0	10,168.0	0.0	1,028.0	11,196.0	2,247.0	0.0	2,122.0	4,368.0	.819	--	.326	.719	15,820.0	14,082.0	10,947.0	.692	949.0
Mean	477.5	0.0	121.1	598.6	391.1	0.0	39.5	430.6	86.4	0.0	81.6	168.0	.819	--	.326	.719	608.5	541.6	421.0	.692	36.5
Month	14,801.0	0.0	3,755.0	18,557.0	12,123.0	0.0	1,226.0	13,349.0	2,679.0	0.0	2,530.0	5,208.0	.819	--	.326	.719	18,862.0	16,790.0	13,052.0	.692	1,132.0

[1] All data in megajoules

[2] Performance based on 71.3 m^3 flat plate absorber area

Table 11. CSU Solar House I: System Performance for Month of February, 1977

	SPACE HEATING, SPACE COOLING, AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collecting	Heat Delivered	Average Efficiency	Heat Lost to Conditioned Space
1																					
2	385.9	0.0	131.4	517.3	385.9	0.0	37.6	423.5	0.0	0.0	93.8	93.8	1.0	0.0	.286	.108	568.8	559.9	439.4	.772	49.4
3	340.9	0.0	91.4	432.3	340.9	0.0	66.7	407.6	0.0	0.0	24.7	24.7	1.0	0.0	.729	.943	910.4	869.3	683.7	.751	61.0
4	470.0	0.0	112.3	582.3	471.8	0.0	79.6	551.4	7.1	0.0	32.7	39.8	.985	0.0	.709	.947	912.3	880.3	663.0	.727	74.5
5	816.9	0.0	106.1	92.3	816.9	0.0	44.1	861.0	0.0	0.0	62.0	62.0	1.0	0.0	.415	.933	300.5	242.7	107.7	.358	58.7
6	430.8	0.0	106.6	537.4	430.8	0.0	47.2	478.0	0.0	0.0	59.4	59.4	1.0	0.0	.443	.899	792.2	761.9	631.6	.797	46.9
7	292.1	0.0	102.5	394.6	292.1	0.0	33.6	325.7	0.0	0.0	68.9	68.9	1.0	0.0	.328	.825	889.2	856.6	692.0	.778	61.9
8	230.6	0.0	103.7	334.3	230.6	0.0	67.6	298.2	0.0	0.0	36.1	36.1	1.0	0.0	.652	.923	868.6	839.4	684.0	.787	77.1
9	79.6	0.0	81.5	161.1	79.6	0.0	32.2	111.8	0.0	0.0	49.3	49.3	1.0	0.0	.395	.695	961.7	921.5	678.4	.705	81.1
10	165.7	0.0	100.2	265.9	166.0	0.0	46.9	212.9	0.0	0.0	53.3	53.3	1.0	0.0	.468	.801	922.1	876.9	657.0	.712	72.1
11	172.2	0.0	103.1	275.3	136.0	0.0	53.3	189.3	36.2	0.0	49.8	86.0	.790	0.0	.517	.688	582.3	507.6	368.7	.633	40.3
12	302.3	0.0	69.5	371.8	302.3	0.0	22.1	324.4	0.0	0.0	47.4	47.4	1.0	0.0	.319	.873	435.5	394.5	286.5	.632	42.1
13	292.0	0.0	121.6	413.6	292.0	0.0	104.4	396.4	0.0	0.0	17.2	17.2	1.0	0.0	.859	.958	746.7	727.2	614.0	.822	50.3
14	353.9	0.0	110.9	464.8	353.9	0.0	74.2	428.1	0.0	0.0	36.7	36.7	1.0	0.0	.669	.921	403.0	278.7	136.4	.339	46.7
15	281.9	0.0	149.2	431.1	281.9	0.0	33.2	315.1	0.0	0.0	116.0	116.0	1.0	0.0	.223	.731	268.5	191.0	136.1	.507	29.3
16																					
17																					
18																					
19																					
20																					
21																					
22																					
23																					
24																					
25	336.3	0.0	57.8	394.1	336.3	0.0	30.9	367.2	0.0	0.0	26.9	26.9	1.0	0.0	.534	.932	447.6	418.1	221.0	.494	35.2
26	360.0	0.0	130.4	490.4	360.0	0.0	0.0	360.0	0.0	0.0	130.4	130.4	1.0	0.0	0.0	.734	315.9	33.8	30.2	.095	19.1
27	589.1	0.0	133.5	722.6	183.1	0.0	0.0	183.1	406.0	0.0	133.5	539.5	.311	0.0	0.0	.253	693.6	597.0	509.1	.734	15.2
28	197.1	0.0	97.8	294.9	197.1	0.0	20.2	217.3	0.0	0.0	77.6	77.6	1.0	0.0	.206	.737	940.0	920.2	766.8	.816	38.5
Total	6,097.6	0.0	1,909.5	8,007.1	5,657.6	0.0	794.0	6,451.6	449.0	0.0	1,115.5	1,565.5	0.928	0.0	0.416	0.806	11,958.9	10,876.2	8,305.6	0.695	899.3
Mean	338.8	0.0	106.1	444.8	314.3	0.0	44.1	358.4	24.9	0.0	62.0	87.0	0.928	0.0	0.416	0.806	664.4	604.2	461.4	0.695	50.0
Month	9,485.2	0.0	2,970.3	12,455.5	8,800.7	0.0	1,235.1	10,035.8	698.4	0.0	1,735.2	2,435.2	0.928	0.0	0.416	0.806	18,602.7	16,916.5	12,919.8	0.695	1,398.9

[1] All data in megajoules

[2] Performance based on 39.9 m^2 evacuated tube absorber area

Table 12. CSU Solar House I: System Performance for Month of March, 1977

	SPACE HEATING, SPACE COOLING, AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collect-ing	Heat Deliv-ered	Average Effi-ciency	Heat Lost to Condi-tioned Space
1	51.3	0.0	75.5	126.8	53.1	0.0	48.0	101.1	0.0	0.0	27.5	27.5	1.0	0.0	.636	.797	819.2	792.3	724.4	.884	73.5
2	268.7	0.0	99.1	367.8	268.7	0.0	0.0	268.7	0.0	0.0	99.1	99.1	1.0	0.0	0.0	.731	138.4	0.0	0.0	0.000	58.9
3	258.7	0.0	304.7	563.4	258.7	0.0	46.0	304.7	0.0	0.0	78.3	78.3	1.0	0.0	.370	.541	727.3	681.4	651.3	.895	40.1
4	233.8	0.0	101.7	335.5	233.8	0.0	44.0	277.8	0.0	0.0	57.7	57.7	1.0	0.0	.433	.828	976.8	951.0	837.3	.857	53.9
5	237.7	0.0	115.3	353.0	237.7	0.0	63.6	301.3	0.0	0.0	51.7	51.7	1.0	0.0	.552	.854	666.2	639.5	481.4	.723	60.2
6	160.7	0.0	198.8	359.5	160.7	0.0	87.8	248.4	0.0	0.0	111.0	111.0	1.0	0.0	.442	.691	994.1	975.0	884.8	.890	66.5
7	49.6	0.0	147.3	196.9	49.6	0.0	86.6	136.2	0.0	0.0	60.7	60.7	1.0	0.0	.588	.692	811.5	703.0	478.9	.673	76.4
8	11.5	0.0	93.6	105.1	4.6	0.0	89.0	93.6	6.9	0.0	37.7	44.6	.402	0.0	.703	.891	860.8	838.1	723.4	.840	68.1
9	20.4	0.0	160.5	80.9	20.4	0.0	114.6	135.0	0.0	0.0	45.9	45.9	1.0	0.0	.714	.746	666.1	653.7	473.8	.711	65.3
10	313.0	0.0	43.5	356.5	313.0	0.0	4.0	317.0	0.0	0.0	39.5	39.5	1.0	0.0	.093	.889	82.0	2.3	4.0	.049	66.5
11	818.7	0.0	79.0	897.7	310.6	0.0	27.3	337.9	508.1	0.0	51.7	559.8	.379	0.0	.345	.376	252.9	50.7	27.3	.108	15.2
12	379.9	0.0	109.2	507.1	46.1	0.0	71.6	117.7	351.8	0.0	37.6	389.4	.116	0.0	.656	.232	1,050.5	1,041.5	1,043.1	.993	37.2
13	123.6	0.0	106.5	230.1	123.6	0.0	78.5	202.1	0.0	0.0	28.0	28.0	1.0	0.0	.737	.878	1,045.3	1,031.2	839.9	.803	69.6
14	61.9	0.0	115.6	177.5	61.9	0.0	90.0	151.9	0.0	0.0	25.6	25.6	1.0	0.0	.779	.856	618.9	582.2	491.9	.795	73.5
15	194.8	0.0	93.4	288.2	194.8	0.0	76.9	271.7	0.0	0.0	16.5	16.5	1.0	0.0	.823	.943	851.5	803.0	526.3	.618	61.3
16																					
17	79.3	0.0	134.7	214.0	79.3	0.0	107.0	186.3	0.0	0.0	27.7	27.7	1.0	0.0	.794	.871	411.2	365.5	186.8	.454	70.0
18	203.5	0.0	73.5	277.0	203.5	0.0	58.0	261.5	0.0	0.0	15.5	15.5	1.0	0.0	.789	.944	443.7	392.2	245.3	.553	53.1
19	336.0	0.0	118.1	454.1	336.0	0.0	81.4	417.4	0.0	0.0	36.7	36.7	1.0	0.0	.689	.919	899.5	854.2	757.1	.842	51.1
20	350.8	0.0	99.9	450.7	350.8	0.0	67.3	418.1	0.0	0.0	32.6	32.6	1.0	0.0	.673	.928	813.4	759.1	700.6	.861	60.5
21	282.5	0.0	90.2	373.3	282.5	0.0	74.6	357.1	0.0	0.0	15.6	15.6	1.0	0.0	.827	.958	944.2	921.4	791.0	.838	62.3
22	77.7	0.0	46.1	123.8	77.7	0.0	30.5	108.2	0.0	0.0	15.6	15.6	1.0	0.0	.661	.874	1,023.9	1,005.2	698.3	.682	72.6
23	46.6	0.0	15.6	62.2	46.6	0.0	0.0	46.6	0.0	0.0	15.6	15.6	1.0	0.0	0.0	.749	835.0	835.0	474.0	.568	63.5
24	0.0	0.0	24.9	24.9	0.0	0.0	.9	.9	0.0	0.0	24.0	24.0	--	0.0	.034	.036	352.5	352.5	165.1	.468	62.8
25	0.0	0.0	77.9	77.9	0.0	0.0	50.6	50.6	0.0	0.0	27.3	27.3	--	0.0	.650	.650	888.2	870.4	753.4	.848	74.1
26	68.9	0.0	82.9	151.8	68.9	0.0	63.3	132.3	0.0	0.0	19.6	19.6	1.0	0.0	.764	.887	738.9	718.8	564.5	.764	74.1
27	90.4	0.0	121.5	211.9	90.4	0.0	52.4	142.8	0.0	0.0	69.1	69.1	1.0	0.0	.431	.674	925.0	903.9	819.2	.886	73.4
28	386.6	0.0	103.9	490.5	386.6	0.0	70.5	457.1	0.0	0.0	33.4	33.4	1.0	0.0	.679	.932	786.0	748.4	570.7	.726	70.6
29	538.3	0.0	217.9	765.2	538.3	0.0	202.3	740.6	0.0	0.0	15.6	15.6	1.0	0.0	.929	.979	426.3	314.5	275.6	.647	31.2
30	200.8	0.0	116.8	317.6	200.8	0.0	66.7	267.5	0.0	0.0	50.1	50.1	1.0	0.0	.571	.842	987.7	977.3	956.0	.968	35.5
31	153.9	0.0	121.2	275.1	153.9	0.0	105.7	259.6	0.0	0.0	15.5	15.5	1.0	0.0	.872	.944	771.1	760.5	643.0	.834	59.5
Total	6,018.0	0.0	3,289.0	9,037.0	5,153.0	0.0	1,959.0	7,112.0	867.0	0.0	1,182.0	2,049.0	.856	0.0	.596	.764	21,708.0	20,532.0	16,788.0	.733	1,800.0
Mean	200.6	0.0	109.6	310.2	171.8	0.0	65.3	237.1	28.9	0.0	39.4	68.3	.856	0.0	.596	.764	723.6	684.4	559.6	.773	60.0
Month	6,218.0	0.0	3,398.0	9,617.0	5,324.0	0.0	2,024.0	7,349.0	896.0	0.0	1,222.0	2,117.0	.856	0.0	.596	.764	22,432.0	21,216.0	17,348.0	.773	1,860.0

[1] All data in megajoules

[2] Performance based on 39.9 m^2 evacuated tube absorber area

Table 13. CSU Solar House I: System Performance for Month of April, 1977

	SPACE HEATING, SPACE COOLING, AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collecting	Heat Delivered	Average Efficiency	Heat Lost to Conditioned Space
1	241.3	0.0	99.3	342.4	243.1	0.0	88.7	331.8	0.0	0.0	10.6	10.6	1.0	0.0	.893	.969	414.7	404.7	219.8	.530	61.8
2	322.3	0.0	116.3	438.6	322.3	0.0	1.9	324.2	0.0	0.0	114.4	114.4	1.0	0.0	.016	.739	263.9	7.4	1.9	.007	34.7
3	387.7	0.0	171.6	559.3	171.0	0.0	0.0	171.0	216.8	0.0	171.6	388.4	.441	0.0	0.0	.305	1,024.0	0.0	0.0	.0000	8.7
4	472.0	0.0	228.2	655.2	23.2	0.0	164.0	187.2	201.9	0.0	64.2	266.1	.054	0.0	.719	.286	557.8	542.2	375.8	.641	17.8
5																					
6																					
7	0.0	0.0	262.4	262.4	0.0	0.0	198.4	198.4	0.0	0.0	64.0	64.0	--	0.0	.756	.756	950.0	950.0	744.2	.783	75.9
8	0.0	0.0	298.6	298.6	0.0	0.0	202.5	202.5	0.0	0.0	96.1	96.1	--	0.0	.678	.678	603.6	603.6	454.2	.752	74.3
9	0.0	0.0	245.5	245.5	0.0	0.0	169.8	169.8	0.0	0.0	75.7	75.7	--	0.0	.692	.692	694.4	656.9	553.3	.797	73.4
10	0.0	0.0	296.9	296.9	0.0	0.0	176.0	176.0	0.0	0.0	120.9	120.9	--	0.0	.593	.652	413.5	371.3	259.7	.628	74.1
11	0.0	0.0	117.6	117.6	0.0	0.0	1.8	1.8	0.0	0.0	115.8	115.8	--	0.0	.015	.015	51.0	9.0	1.7	.033	70.4
12	0.0	0.0	122.0	122.0	0.0	0.0	59.4	59.4	0.0	0.0	62.6	62.9	--	0.0	.487	.487	149.0	145.9	59.4	.399	62.2
13	0.0	0.0	115.0	115.0	0.0	0.0	36.4	36.4	0.0	0.0	78.6	78.6	--	0.0	.316	.317	120.0	95.4	36.4	.303	55.3
14	9.6	0.0	212.1	221.7	9.6	0.0	153.9	163.5	0.0	0.0	58.2	58.2	1.0	0.0	.726	.737	291.0	288.4	169.1	.581	50.4
15	133.7	0.0	99.5	233.2	133.7	0.0	0.0	133.7	0.0	0.0	99.5	99.5	1.0	0.0	0.0	.573	47.8	0.0	0.0	0.000	42.6
16	61.1	0.0	215.2	276.3	61.1	0.0	146.3	207.4	0.0	0.0	68.9	68.9	1.0	0.0	.680	.751	266.1	263.0	165.3	.621	27.5
17	23.6	0.0	245.0	268.6	23.6	0.0	172.7	196.3	0.0	0.0	72.3	72.3	1.0	0.0	.705	.713	302.5	299.7	227.2	.751	29.6
18	45.5	0.0	121.5	42.0	45.5	0.0	-3.5	42.0	0.0	0.0	125.0	167.0	1.0	0.0	0.000	.272	35.1	0.6	-3.5	0.000	31.2
19	82.6	0.0	107.6	190.2	82.6	0.0	12.0	94.6	0.0	0.0	95.6	95.6	1.0	0.0	.111	.497	58.0	34.6	12.0	.347	19.0
20	63.1	0.0	269.4	332.5	56.0	0.0	213.5	269.5	7.1	0.0	55.9	63.0	.887	0.0	.793	.811	261.4	256.3	55.2	.211	27.3
21	19.2	0.0	259.7	278.9	17.4	0.0	214.9	232.2	1.8	0.0	44.8	46.6	.907	0.0	.827	.833	1,057.3	1,044.9	797.7	.754	59.5
22	28.8	0.0	330.4	359.9	28.8	0.0	218.1	246.9	0.0	0.0	112.3	112.3	1.0	0.0	.660	.687	945.3	938.2	808.3	.855	74.3
23	0.0	0.0	298.4	298.4	0.0	0.0	251.1	251.1	0.0	0.0	47.3	47.3	--	0.0	.842	.841	989.1	980.2	708.9	.717	75.9
24																					
25																					
26																					
27																					
28																					
29																					
30																					
31																					
Total	1,847.0	0.0	4,133.0	5,980.0	1,218.0	0.0	2,478.0	3,696.0	428.0	0.0	1,754.0	2,182.0	.659	0.0	.600	.618	9,495.5	7,892.3	5,624.0	.592	1,046.0
Mean	88.0	0.0	196.8	284.8	58.0	0.0	58.0	176.0	20.4	0.0	83.5	103.9	.659	0.0	.600	.618	452.2	375.8	267.8	.592	49.8
Month	2,639.0	0.0	5,904.0	8,543.0	1,740.0	0.0	3,540.0	5,280.0	611.0	0.0	2,506.0	3,117.0	.659	0.0	.600	.618	13,565.0	11,247.7	8,034.0	.592	1,494.0

[1] All data in megajoules

[2] Performance based on 39.9 m^2 evacuated tube absorber area

Table 14. CSU Solar House I: System Performance for Month of August, 1977

	SPACE HEATING, SPACE COOLING, AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collecting	Heat Delivered	Average Efficiency	Heat Lost to Conditioned Space
1	0.0	1,020.2	89.4	1,109.6	0.0	652.7	47.4	700.1	0.0	367.6	42.0	409.6	--	.640	.531	.631	798.0	794.0	491.6	.615	61.0
2	0.0	1,133.3	123.0	1,256.3	0.0	624.3	74.6	698.9	0.0	509.0	48.4	557.4	--	.551	.607	.556	945.6	941.6	508.6	.538	60.7
3																					
4	0.0	729.5	241.1	970.6	0.0	242.5	191.5	434.0	0.0	487.1	49.6	536.7	--	.332	.794	.447	538.7	538.7	404.8	.752	55.4
5																					
6	0.0	762.1	226.9	989.0	0.0	590.1	181.8	771.9	0.0	172.0	45.1	217.1	--	.774	.801	.780	941.6	941.6	772.4	.820	61.3
7	0.0	926.8	223.0	1,149.8	0.0	498.9	185.2	684.1	0.0	427.9	37.8	465.7	--	.538	.831	.595	790.0	790.8	631.3	.798	59.5
8	0.0	1,070.2	210.9	1,281.1	0.0	195.4	155.5	350.9	0.0	874.8	55.4	930.2	--	.183	.737	.274	486.8	474.8	352.2	.723	53.9
9	0.0	1,156.3	174.4	1,330.7	0.0	489.6	94.4	584.0	0.0	666.7	80.0	746.7	--	.423	.541	.439	853.9	841.9	574.6	.673	57.3
10																					
11	0.0	500.1	112.9	613.0	0.0	0.0	52.2	52.2	0.0	500.1	60.7	560.8	--	0.000	.462	.085	283.3	131.7	91.9	.324	50.2
12	0.0	822.2	82.6	904.8	0.0	459.1	39.1	498.2	0.0	363.1	43.5	406.6	--	.558	.473	.551	909.7	814.0	355.1	.391	56.6
13	0.0	1,041.7	97.0	1,138.7	0.0	409.2	46.2	455.4	0.0	632.5	50.8	683.3	--	.393	.476	.400	810.0	726.1	376.1	.463	56.4
14																					
15																					
16																					
17																					
18																					
19	0.0	864.2	66.1	930.3	0.0	0.0	66.1	66.1	0.0	864.2	50.6	914.8	--	0.000	.566	.071	139.5	111.3	77.0	.552	57.4
20	0.0	832.6	145.3	977.9	0.0	732.2	67.5	799.7	0.0	100.3	77.8	178.1	--	.880	.464	.818	969.6	961.6	681.3	.704	64.9
21	0.0	812.5	168.5	981.0	0.0	352.0	119.4	471.4	0.0	460.5	49.1	509.6	--	.433	.709	.481	662.3	634.4	415.1	.627	55.4
22																					
23																					
24	0.0	919.4	142.8	1,062.2	0.0	501.3	99.2	600.5	0.0	418.1	43.6	461.7	--	.545	.695	.565	833.9	821.9	585.5	.704	58.1
25																					
26																					
27																					
28	0.0	6.9	157.3	164.2	0.0	6.9	91.8	98.7	0.0	0.0	65.5	65.5	--	1.000	.583	.601	654.4	602.5	407.8	.625	62.2
29																					
30																					
31																					
Total	0.0	12,598.0	2,261.0	14,859.0	0.0	5,754.0	1,512.0	7,266.0	0.0	6,844.0	800.0	7,644.0	--	.457	.669	.489	10,617.0	10,027.0	6,725.0	.633	870.0
Mean	0.0	840.0	150.7	990.7	0.0	383.6	100.8	484.4	0.0	456.3	53.3	509.6	--	.457	.669	.489	707.8	668.5	448.4	.633	58.0
Month	0.0	26,036.0	4,673.0	30,709.0	0.0	11,892.0	3,125.0	15,017.0	0.0	14,144.0	1,653.0	15,797.0	--	.457	.669	.489	21,942.0	20,722.0	13,899.0	.633	1,799.0

[1] All data in megajoules

[2] Performance based on 39.9 m^2 evacuated tube absorber area

Table 15. CSU Solar House I: System Performance for Month of September, 1977

	SPACE HEATING, SPACE COOLING, AND DOMESTIC HOT WATER HEATING[1]																COLLECTOR PERFORMANCE[1,2]				
	Energy Required				Solar Energy Used				Auxiliary Heat Used				Solar Fraction								
Day	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Space Heating	Space Cooling	Hot Water Heating	Total	Total Solar	Solar When Collect-ing	Heat Deliv-ered	Average Effi-ciency	Heat Lost to Condi-tioned Space
1	0.0	701.6	110.4	812.0	0.0	520.5	47.8	568.3	0.0	181.1	62.6	243.6	--	.742	.433	.700	812.3	792.5	564.6	.695	58.3
2																					
3	0.0	750.0	162.3	912.3	0.0	0.0	89.2	89.2	0.0	750.0	73.1	823.1	--	.000	.550	.098	503.5	483.0	338.3	.672	55.3
4	0.0	938.2	81.4	1,019.6	0.0	726.4	40.1	766.5	0.0	211.8	41.3	253.1	--	.774	.493	.752	1,001.8	990.0	679.7	.678	64.6
5	0.0	1,030.6	126.3	1,156.9	0.0	634.2	50.5	684.7	0.0	396.3	75.8	472.1	--	.615	.400	.592	1,009.2	997.5	692.7	.686	60.7
6	0.0	1,169.9	111.6	1,281.5	0.0	662.8	45.3	708.1	0.0	507.1	66.3	573.4	--	.567	.406	.553	993.3	981.3	726.5	.731	61.5
7	0.0	980.5	94.6	1,075.1	0.0	583.6	47.3	630.9	0.0	396.9	47.3	444.2	--	.595	.500	.587	907.6	892.5	639.1	.704	67.7
8	0.0	1,081.6	90.2	1,171.8	0.0	552.1	47.9	600.0	0.0	529.5	42.3	571.8	--	.510	.531	.512	932.7	918.4	607.6	.651	59.3
9	0.0	596.4	103.9	700.3	0.0	535.4	51.6	587.0	0.0	61.0	52.3	113.3	--	.898	.497	.838	928.9	886.4	623.4	.671	59.4
10	0.0	667.9	125.9	793.8	0.0	475.1	67.6	542.7	0.0	192.8	58.3	251.1	--	.711	.537	.684	821.4	796.2	560.7	.683	58.1
11																					
12	0.0	861.1	92.6	953.7	0.0	187.1	46.9	234.0	0.0	674.1	45.7	719.8	--	.217	.507	.245	1,011.9	981.7	328.8	.627	52.1
13	0.0	250.6	147.3	397.9	0.0	136.6	63.9	200.5	0.0	114.1	83.4	197.5	--	.545	.434	.504	1,030.1	1,006.3	740.4	.732	57.0
14	0.0	0.0	100.0	100.0	0.0	0.0	51.4	51.4	0.0	0.0	48.6	48.6	--	--	.514	.514	538.6	507.0	729.1	.708	63.0
15																					
16																					
17																					
18																					
19																					
20																					
21																					
22																					
23	0.0	145.8	105.3	251.1	0.0	145.8	35.2	181.0	0.0	0.0	70.1	70.1	--	.916	.339	.721	1,071.3	992.2	649.1	.606	65.1
24	0.0	346.8	116.7	463.5	0.0	346.8	49.1	395.9	0.0	0.0	67.6	67.6	--	1.000	.334	.854	1,012.0	953.0	634.4	.627	72.3
25	0.0	408.8	80.3	489.1	0.0	408.6	41.0	449.6	0.0	0.0	39.3	39.3	--	1.000	.421	.919	1,119.7	1,098.8	737.0	.658	69.0
26																					
27																					
28																					
29	0.0	820.0	116.3	936.3	0.0	820.0	43.8	863.8	0.0	0.0	72.8	72.8	--	1.000	.376	.922	712.0	671.7	453.2	.636	58.3
30	0.0	102.0	128.2	230.2	0.0	102.0	29.5	131.5	0.0	0.0	98.7	98.7	--	1.000	.230	.571	360.4	241.5	82.7	.229	53.1
31																					
Total	0.0	10,852.0	1,893.0	12,745.0	0.0	6,837.0	848.0	7,685.0	0.0	4,015.0	1,046.0	5,061.0	--	.630	.448	.603	14,767.0	14,170.0	9,787.0	.663	1,035.0
Mean	0.0	638.4	111.4	749.8	0.0	402.2	49.9	452.1	0.0	236.2	61.5	297.7	--	.630	.448	.603	868.6	833.5	575.7	.663	60.9
Month	0.0	19,151.0	3,340.0	22,491.0	0.0	12,065.0	1,497.0	13,562.0	0.0	7,085.0	1,845.0	8,930.0	--	.630	.448	.603	26,059.0	25,006.0	17,272.0	.663	1,826.0

[1]All data in megajoules

[2]Performance based on 39.9 m^2 evacuated tube absorber area

evacuated tube collector system with 39.9 square meters of absorber area. The respective overall areas occupied by these collectors are 71.3 and 75.2 sq meters.

The total energy required is determined from the flow rates and temperature differences across the particular load, and the flow rate of natural gas to the hot water heater. The space heating load is the energy supplied to the heating coil plus the loss from the solar storage tank into the house. The total space cooling load is the normal residential cooling load plus the loss from the solar storage. The energy required for space cooling is the energy supplied to the Arkla chiller. The solar energy used for hot water heating is the energy supplied from the collector loop to the solar preheat tank, the auxiliary energy used for hot water heating is the energy content of the natural gas supplied to the hot water heater at an efficiency of 82 percent, and the total energy required for hot water heating is the sum of these two quantities.

Monthly totals and daily averages based on the actual number of days with good data appear in the monthly performance summaries, Tables 16 through 24. Both the totals and the means are presented based on absorber area and total roof area occupied by the solar collectors. Four additional data items beyond those already identified appear in the tables. The average daily energy flux is simply the average daily solar radiation incident on one square meter. Storage energy gain during data gaps in the change is storage energy over days for which no data is available. The total apparent energy delivered to storage includes this energy change. The net storage energy gain for the month is the change in storage energy from the first day to the last day of the month, accounting for residual energy from the previous month and any remaining energy at the end of the month.

Table 16

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

October, 1976

	Monthly Totals	Daily Averages
Days of Data	28	28
Average Daily Energy Flux	20.6	20.6
Total Incident Solar on 67 m^2 absorber	42,288.0	
Total Incident Solar on 71.3 m^2 collector area	43,534.0	
Incident Solar "ON" (absorber area)	27,595.0	890.2
Incident Solar "ON" (collector area)	29,366.0	946.3
Energy Delivered to Storage	5,934	191.4
Net Energy Gain During Data Gaps	451.	14.5
Apparent Energy Delivered to Storage	6,385.	205.0
% Solar Collection Efficiency based on Total Incident (collector area)	13.0	13.0
% Solar Collection Efficiency based on Solar "ON" (collector area)	20.2	20.2
Net Storage Energy Gain for Month	232.1	7.5
Space Heating Load (coil)	77	2.5
Space Heating by Solar (coil)	72	2.3
% Solar Space Heating (coil)	92.9	92.9
Solar Loss from Storage	1,941.6	62.6
Total Space Heating Load	2,017.6	65.1
Total Solar Space Heating	2,012.6	64.9
% Solar Space Heating	99.8	99.8
Energy to Space Cooling	4,189.	135.1
Solar Energy to Space Cooling	2,203.	71.1
% Solar Space Cooling	47.4	47.4
Total Energy to Service HW	5,974	192.7
Solar Energy to Service HW	1,465	47.2
% Solar Hot Water	24.5	24.5
Total Load	12,181.6	393.0
Total Load by Solar	5,680.6	183.3
% Solar Total	46.6	.365

All data in megajoules

Table 17

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

November, 1976

	Monthly Totals	Daily Averages
Days of Data	25	25
Average Daily Energy Flux	15.4	15.4
Total Incident Solar on 67 m^2 absorber area	31,893	1,063.1
Total Incident Solar on 71.3 m^2 collector area	19,438.	647.9
Energy Delivered to Storage	5,467	182.2
Net Energy Gain During Data Gaps	-399.	-12.9
Apparent Energy Delivered to Storage	5,068.	168.9
% Solar Collection Efficiency based on Total Incident (collector area)	13.8	13.8
% Solar Collection Efficiency based on Solar "ON" (collector area)	22.7	22.7
Net Storage Energy Gain for Month	-769	-25.6
Space Heating Load (coil)	4,775	159.2
Space Heating by Solar (coil)	2,204	73.5
% Solar Space Heating (coil)	46.1	46.1
Solar Loss from Storage	1,143	38.1
Total Space Heating Load	5,918	197.3
Total Solar Space Heating	3,347	111.6
% Total Solar Space Heating	56.6	56.6
Energy to Space Cooling	104.	3.5
Solar Energy to Space Cooling	104.	3.5
% Solar Space Cooling	100.	100.
Total Energy to Service HW	4,370	145.7
Solar Energy to Service HW	1,361	45.4
% Solar Hot Water	31.1	31.1
Total Load	10,392	346.4
Total Load by Solar	4,812	160.4
% Solar Total	46.3	46.3

All data in megajoules

Table 18

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

December, 1976

	Monthly Totals	Daily Averages
Days of Data	10	10
Average Daily Energy Flux (per m^2)	13.6	13.6
Total Incident Solar on 67 m^2 absorber area	28,345	914.3
Total Incident Solar on 71.3 m^2 collector area	39,164	973.0
Incident Solar "ON" (absorber area)	21,297	687.0
Incident Solar "ON" (collector area)	22,664	731.1
Energy Delivered to Storage	5,880	189.7
Net Energy Gain During Data Gaps	0.0	0.0
Apparent Energy Delivered to Storage	5,880.	189.7
% Solar Collection Efficiency based on Total Incident (collector area)	20.5	20.5
% Solar Collection Efficiency based on Solar "ON" (collector area)	27.3	27.3
Net Storage Energy Gain for Month	295.8	9.5
Space Heating Load (coil)	7,341.	236.8
Space Heating by Solar (coil)	1,060	34.2
% Solar Space Heating (coil)	14.4	14.4
Solar Loss from Storage	1,258	40.6
Total Space Heating Load	8,599	277.4
Total Solar Space Heating	13,251	104.9
% Total Solar Space Heating	37.8	37.8
Energy to Space Cooling	0.0	0.0
Solar Energy to Space Cooling	0.0	0.0
% Solar Space Cooling	-	-
Total Energy to Service HW	3,534.	114.0
Solar Energy to Service HW	1,993	64.3
% Solar Hot Water	56.4	56.4
Total Load	12,133	391.4
Total Load by Solar	5,244	169.2
% Solar Total	43.2	43.2

All data in megajoules

Table 19

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

January, 1977

	Monthly Totals	Daily Averages
Days of Data	26	26
Average Daily Energy Flux	15.3	15.3
Total Incident Solar on 39.9 m^2 absorber area	18,862	608.5
Total Incident Solar on 75.2 m^2 collector area	35,549	1,147
Incident Solar "ON" (absorber area)	16,790	541.6
Incident Solar "ON" (collector area)	31,644	1,020.8
Energy Delivered to Storage	13,052	421.0
Energy Gain During Data Gaps	-717.	-23.1
Apparent Energy Delivered to Storage	12,335.	397.9
% Solar Collection Efficiency based on Total Incident (collector area)	36.7	36.7
% Solar Collection Efficiency based on Solar "ON" (collector area)	41.2	41.2
Net Storage Energy Gain for Month	815	26.3
Space Heating Load (coil)	14,801	477.5
Space Heating by Solar (coil)	12,123	391.1
% Solar Space Heating (coil)	81.0	81.9
Solar Loss from Storage	1,132	36.5
Total Space Heating Load	15,933	514
Total Solar Space Heating	13,255	427.6
% Total Solar Space Heating	83.2	83.2
Energy to Space Cooling	0.0	0.0
Solar Energy to Space Cooling	0.0	0.0
% Solar Space Cooling	-	-
Total Energy to Service HW	3,755	121.1
Solar Energy to Service HW	1,226	39.5
% Solar Hot Water	32.6	32.6
Total Load	19,688	635.1
Total Load by Solar	14,481	467.1
% Solar Total	73.6	73.6

All data in megajoules

Table 20

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

February, 1977

	Monthly Totals	Daily Averages
Days of Data	18	18
Average Daily Energy Flux	16.6	16.6
Total Incident Solar on 39.9 m^2 observer area	18,602.7	664.4
Total Incident Solar on 75.2 m^2 collector area	35,060.7	1,252.2
Incident Solar "ON" (39.9 m^2 absorber area)	16,918.5	604.2
Incident Solar "ON" (collector area)	31,886.5	1,138.8
Energy Delivered to Storage	12,919.8	461.4
Net Energy Gain During Data Gaps	493.	17.6
Apparent Energy Delivered to Storage	13,413.	479.0
% Solar Collection Efficiency based on Total Incident (collector area)	36.9	36.9
% Solar Collection Efficiency based on Solar "ON" (collector area)	40.3	40.3
Net Storage Energy Gain for Month	-369	-13.2
Space Heating Load (coil)	9,485.2	338.8
Space Heating by Solar (coil)	8,800.7	314.3
% Solar Space Heating (coil)	92.8	92.8
Solar Loss from Storage	1,337	47.8
Total Space Heating Load	14,379	513.6
Total Solar Space Heating	13,763	491.6
% Total Solar Space Heating	95.7	95.7
Energy to Space Cooling	0.0	0.0
Solar Energy to Space Cooling	0.0	0.0
% Solar Space Cooling	-	-
Total Energy to Service HW	2,970.3	106.1
Solar Energy to Service HW	1,235.1	44.1
% Solar Hot Water	41.6	41.6
Total Load	12,455.5	444.8
Total Load by Solar	10,035.8	358.4
% Solar Total	80.6	80.6

All data in megajoules

Table 21

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

March, 1977

	Monthly Totals	Daily Averages
Days of Data	30	30
Average Daily Energy Flux	18.1	18.1
Total Incident Solar on 39.9 m^2 absorber area	22,432	723.6
Total Incident Solar on 75.2 m^2 collector area	42,277	1,363.8
Incident Solar "ON" (absorber area)	21,216	684.4
Incident Solar "ON" (collector area)	39,986	1,289.9
Energy Delivered to Storage	17,348	559.6
Net Energy Gain During Data Gaps	2.	0.1
Apparent Energy Delivered to Storage	17,350.	559.7
% Solar Collection Efficiency based on Total Incident (collector area)	41.0	41.0
% Solar Collection Efficiency based on Solar "ON" (collector area)	43.4	43.4
Net Storage Energy Gain for Month	223	7.2
Space Heating Load (coil)	6,218	200.6
Space Heating by Solar (coil)	5,324	171.8
% Solar Space Heating (coil)	85.6	85.6
Solar Loss from Storage	1,860	60
Total Space Heating Load	8,078	260.6
Total Solar Space Heating	7,184	231.7
% Total Solar Space Heating	88.9	88.9
Energy to Space Cooling	0.0	0.0
Solar Energy to Space Cooling	0.0	0.0
% Solar Space Cooling	-	-
Total Energy to Service HW	3,398	109.6
Solar Energy to Service HW	2,024	65.3
% Solar Hot Water	59.6	59.6
Total Load	11,476	370.2
Total Load by Solar	9,208	297
% Solar Total	80.2	80.2

All data in megajoules

Table 22

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

April, 1977

	Monthly Totals	Daily Averages
Days of Data	21	21
Average Daily Energy Flux	16.0	16.0
Total Incident Solar on 39.9 m^2 absorber area	9,495.5	452.2
Total Incident Solar on 75.2 m^2 collector area	18,169.5	852.3
Incident Solar "ON" (absorber area)	7,892.3	375.8
Incident Solar "ON" (collector area)	14,874.7	708.3
Energy Delivered to Storage	8,034	267.8
Net Energy Gain During Data Gaps	1,036.	34.5
Apparent Energy Delivered to Storage	9,070.	292.6
% Solar Collection Efficiency based on Total Incident (collector area)	44.2	44.2
% Solar Collection Efficiency based on Solar "ON" (collector area)	54.0	54.0
Net Storage Energy Gain for Month	164.	5.5
Space Heating Load	2,639	88.0
Space Heating by Solar	1,740	58.0
% Solar Space Heating	65.9	65.9
Solar Loss from Storage	1,494	49.8
Total Space Heating Load	4,133	137.8
Total Solar Space Heating	3,234	107.8
% Total Solar Space Heating	78.2	78.2
Energy to Space Cooling	0.0	0.0
Solar Energy to Space Cooling	0.0	0.0
% Solar Space Cooling	-	-
Total Energy to Service HW	5,904	196.8
Solar Energy to Service HW	3,540	118.0
% Solar Hot Water	60.0	60.0
Total Load	10,037	334.6
Total Load by Solar	6,774	225.8
% Solar Total	67.5	67.5

All data in megajoules

Table 23

CSU Solar House I Daily Averages and Extrapolated Monthly Totals

August, 1977

	Monthly Totals	Daily Averages
Days of Data	15	15
Average Daily Energy Flux	17.7	17.7
Total Incident Solar on 39.9 m^2 absorber area	21,942	707.8
Total Incident Solar on 75.2 m^2 collector area	41,354	1,334
Incident Solar "ON" (absorber area)	20,722	688.5
Incident Solar "ON" (collector area)	39,056	1,259.9
Energy Delivered to Storage	13,899	772.2
Net Energy During Data Gaps	226.3	7.3
Apparent Energy Delivered to Storage	14,125.	455.7
% Solar Collection Efficiency based on Total Incident (collector area)	33.6	33.6
% Solar Collection Efficiency based on Solar "ON" (collector area)	35.6	35.6
Net Storage Energy Gain for Month	244.	7.9
Space Heating Load	0.0	0.0
Space Heating by Solar	0.0	0.0
% Solar Space Heating	-	-
Solar Loss from Storage	1,799	
Energy to Space Cooling	26,036	840.0
Solar Energy to Space Cooling	11,892	383.6
% Solar Space Cooling	45.7	45.7
Total Energy to Service HW	4,673	150.7
Solar Energy to Service HW	3,125	100.8
% Solar Hot Water	66.9	66.9
Total Load	30,709	990.6
Total Load by Solar	15,016	484.4
% Solar Total	48.9	48.9

All data in megajoules

Table 24

CSU Solar House I Daily Average and Extrapolated Monthly Totals

September, 1977

	Monthly Totals	Daily Averages
Days of Data	17	17
Average Daily Energy Flux	21.8	21.8
Total Incident Solar on 39.9 m^2 absorber area	26,059	868.6
Total Incident Solar on 75.2 m^2 collector area	49,114	1,637.1
Incident Solar "ON" (absorber area)	25,006	833.5
Incident Solar "ON" (collector area)	47,129	1,570.9
Energy Delivered to Storage	17,272	575.7
Net Energy Gain During Data Gaps	-1,131.	-37.7
Apparent Energy Delivered to Storage	16,141.	538.
% Solar Collection Efficiency based on Total Incident (collector area)	35.2	35.2
% Solar Collection Efficiency based on Solar "ON" (collector area)	36.6	36.6
Net Storage Energy Gain for Month	-70.1	-2.3
Space Heating Load	0.0	0.0
Space Heating by Solar	0.0	0.0
% Solar Space Heating	-	-
Solar Loss from Storage	1,826	
Energy to Space Cooling	19,151	638.4
Solar Energy to Space Cooling	12,065	402.2
% Solar Space Cooling	63.0	63.0
Total Energy to Service HW	3,342	111.4
Solar Energy to Service HW	1,497	49.9
% Solar Hot Water	44.8	44.8
Total Load	22,494	749.8
Total Load by Solar	13,562	452.1
% Solar Total	60.3	60.3

All data in megajoules

The annual system performance is summarized in Table 25. The solar fraction for each of the three types of load and the overall solar fraction are presented for the flat-plate system for the time period 1 October 1976 to 31 December 1976. The data for the evacuated tube system pertain to the time period from 1 January 1977 to 30 September 1977.

Table 25

Annual System Performance

System	Space Heating Load	Space Heating Solar Fraction	Space Cooling Load	Space Cooling Solar Fraction
Flat-plate[1]	16,535	0.343	4,293	0.537
Evacuated Tube[2]	39,028	0.866	45,187	0.530

System	Hot Water Heating Load	Hot Water Heating Solar Fraction	Total Load	Total Solar Fraction
Flat-plate[1]	13,851	0.348	34,685	0.427
Evacuated Tube[2]	24,042	0.526	108,257	0.650

[1]For period 1 October 1976 to 31 December 1976
[2]For period 1 January 1977 to 30 September 1977

2.1.2. Supplemental Energy Required

Supplemental energy requirements for space heating and cooling were met by the auxiliary hot water boiler, fueled by natural gas. Supplemental energy for domestic hot water heating was supplied by a conventional natural gas-fired hot water heater. The monthly natural gas and electricity usage is given in Table 26.

Table 26

Monthly Total Natural Gas and Solar System Electric Power* Usage

	Natural Gas			Solar System Electric Power* kWhr
	Auxiliary Boilers (m^3)	Domestic Hot Water (m^3)	Total	
October	112.1	68.8	181.9	728
November	86.1	90.3	176.4	557
December	183.8	102.8	286.6	462
January	153.8	101.1	254.9	700
February	29.7	66.5	96.3	609
March	53.0	41.0	94.0	564
April	43.0	68.6	111.6	346
May	32.0	63.4	95.4	851
June	144.4	37.9	182.3	817
July	716.4	54.6	771.0	1,815
August	585.3	51.3	636.6	1,450
September	324.5	61.5	386.0	1,236
Total	2,463.7	807.9	3,271.6	10,135

*Excludes electric power used by blower and load pump

The criteria used to determine whether the energy supplied to meet the space heating and cooling loads was solar or auxiliary was the position of automatic Valve V2. The determination of solar and auxiliary energy supply to the domestic hot water system was as previously described.

2.1.3. Solar Energy Incident on Collectors

The solar energy incident on the collectors was measued by an Eppley precision pyranometer mounted in the plane of the collectors. The radiation data was integrated to provide accurate measurement during periods of transient radiation. The solar energy incident while the collector was running was determined by the computer during data processing by taking readings of the integrated radiation whenever the collector flow rate was nonzero.

2.1.4. Solar Energy Collected

The solar energy collected was determined from the collector loop flow rate (integrated to account for transients) and the temperatures to and from the collector.

2.1.5. Solar Energy Used

The total solar energy used for heating is the sum of the energy supplied from the storage tank to the load, the energy lost from storage into the house, and the energy input from the collector loop to the domestic hot water preheat tank. Both of these calculations are based on the appropriate flow rates and temperature differences. For cooling the energy lost from storage adds to the cooling load and is met by the energy supplied to the chiller from the storage tank.

2.2 Record of the Quality of Thermal Performance of the System

Figures 7 and 8 show the indoor temperature for a typical series of days in the heating and cooling season, respectively. For the time period shown in Figure 7, the house thermostat was set at 19.5°C (67°F). It may be seen that the average room temperature ranged from 16°C to 22°C (61°F to 72°F) during this period. During the cooling season represented

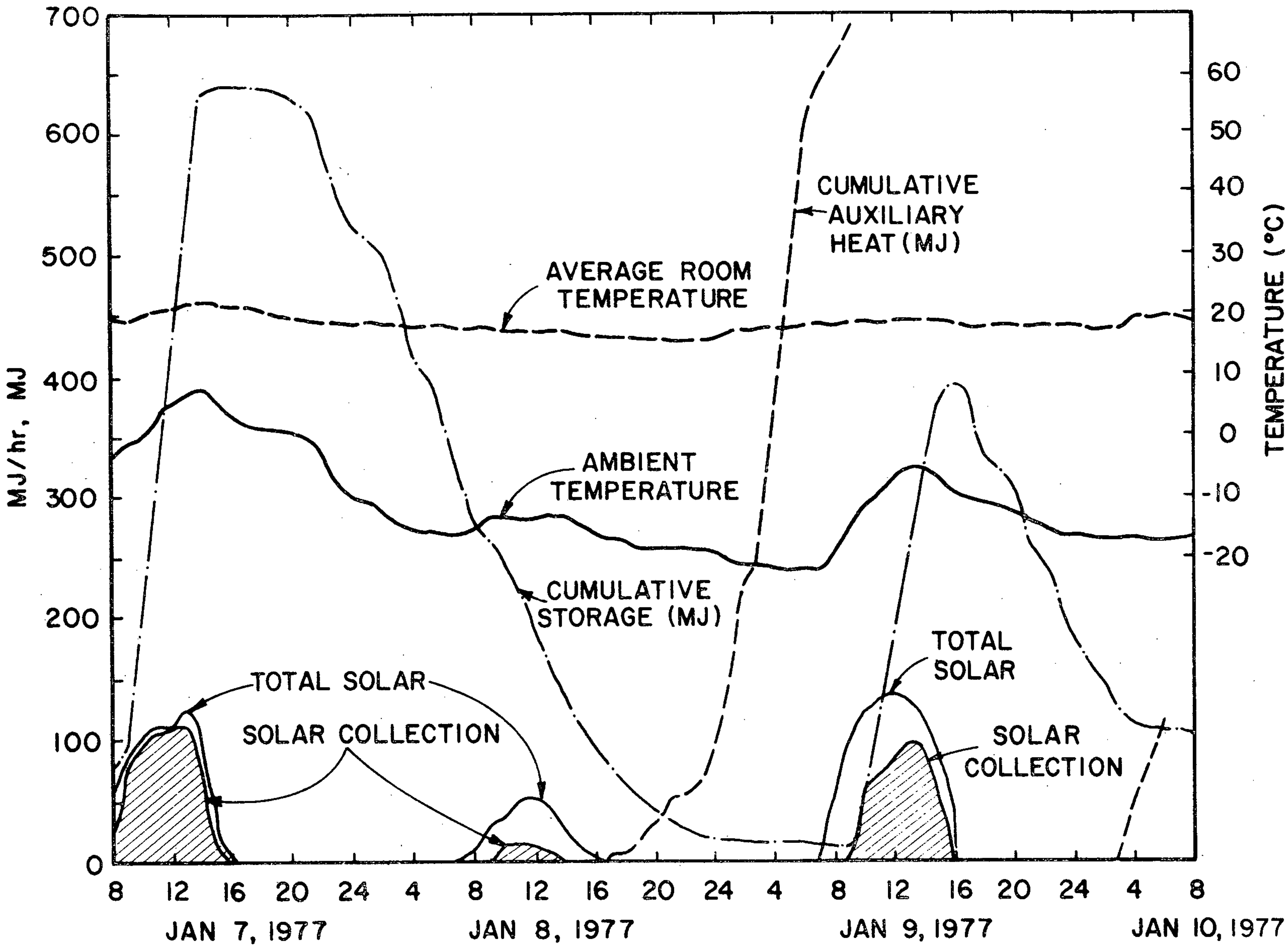
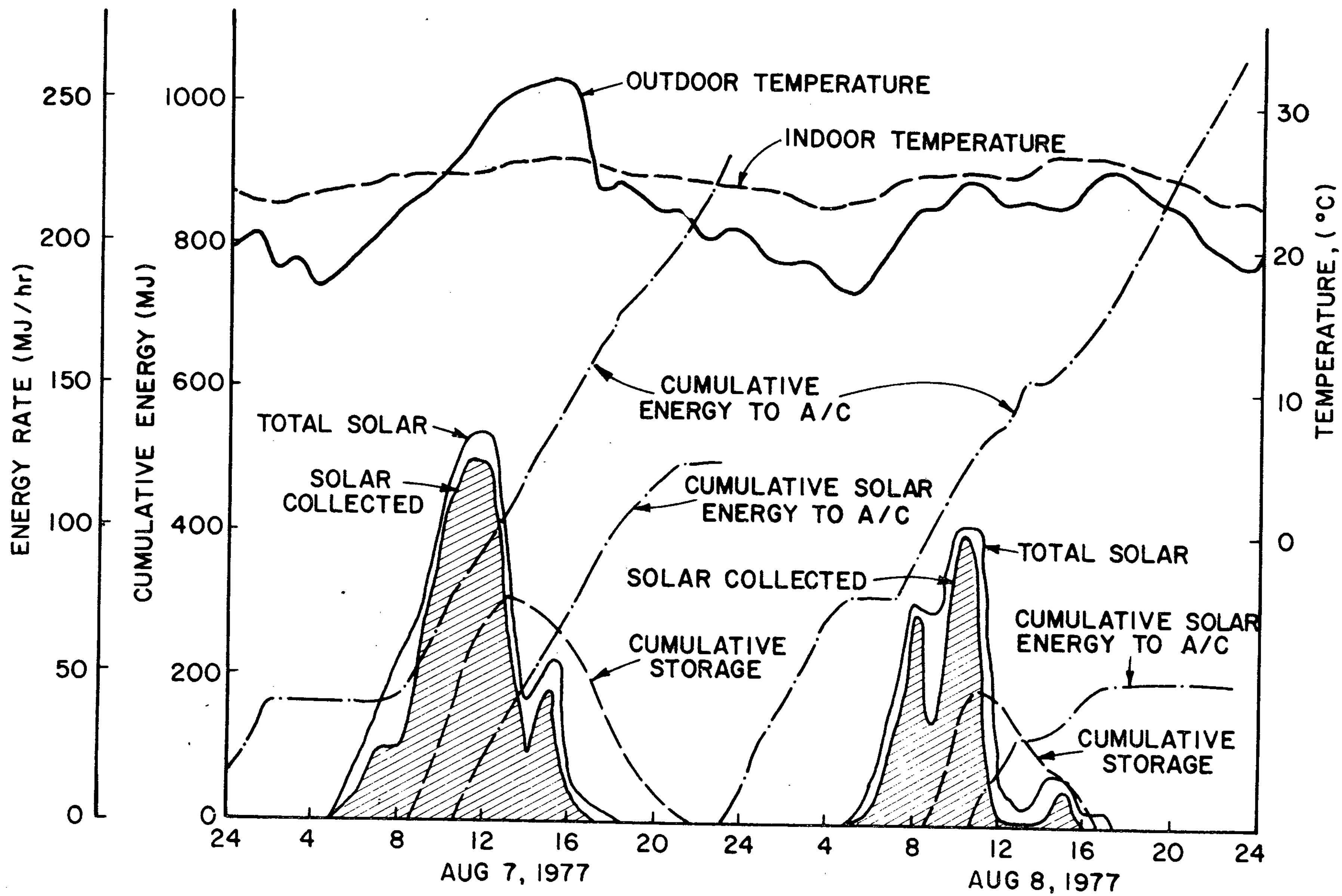


Figure 7. System Performance for January 7 through January 9, 1977


OUTDOOR TEMPERATURE
INDOOR TEMPERATURE
CUMULATIVE ENERGY TO A/C
TOTAL SOLAR
SOLAR COLLECTED
CUMULATIVE SOLAR ENERGY TO A/C
CUMULATIVE STORAGE
TOTAL SOLAR
SOLAR COLLECTED
CUMULATIVE SOLAR ENERGY TO A/C
CUMULATIVE STORAGE
ENERGY RATE (MJ/hr)
0
50
100
150
200
250
CUMULATIVE ENERGY (MJ)
0
200
400
600
800
1000
TEMPERATURE, (°C)
0
10
20
30
24 4 8 12 16 20 24 4 8 12 16 20 24
AUG 7, 1977
AUG 8, 1977

by Figure 8, the house thermostat was set at 22.5°C (72.5°F). The room temperature is seen to vary between 22.5°C and 26°C (72.5°F and 78.8°F) during this period.

2.3 Solar Contribution to Energy Requirements

Daily values of the percent solar contribution to the energy requirements of the three types of load and the overall load appear in the solar fraction portion of Tables 7 through 15. The monthly percentages appear at the bottom of the table, and the monthly load and solar fraction are presented graphically for each month in Figures 9 and 10. The annual fractions appear in Table 25 mentioned previously.

2.4 Monthly and Annual Energy or Fuel Savings

Table 27 shows the monthly and annual quantities of gas heat saved by use of the solar heating and cooling system if the same heating coil and chiller were driven by gas heated hot water. Savings of energy for domestic water heating are tabulated in column [1]. These values are obtained from Tables 16 through 24 by deducting the heat losses from the domestic hot water solar preheat tank and dividing the differences by the combustion efficiency of the auxiliary domestic hot water unit.

Energy savings for space heating (Column [2]) correspond to the useful solar energy delivered to thermal storage for all heating purposes, less that used for domestic hot water heating (heat losses from storage and piping being useful for space heating) divided by the combustion efficiency of the auxiliary boiler. Solar heat losses from the domestic hot water preheat tank also contribute to meeting the heating load and the resulting savings are included in the figures in Column [2], except in the month of October, which primarily had a cooling load.

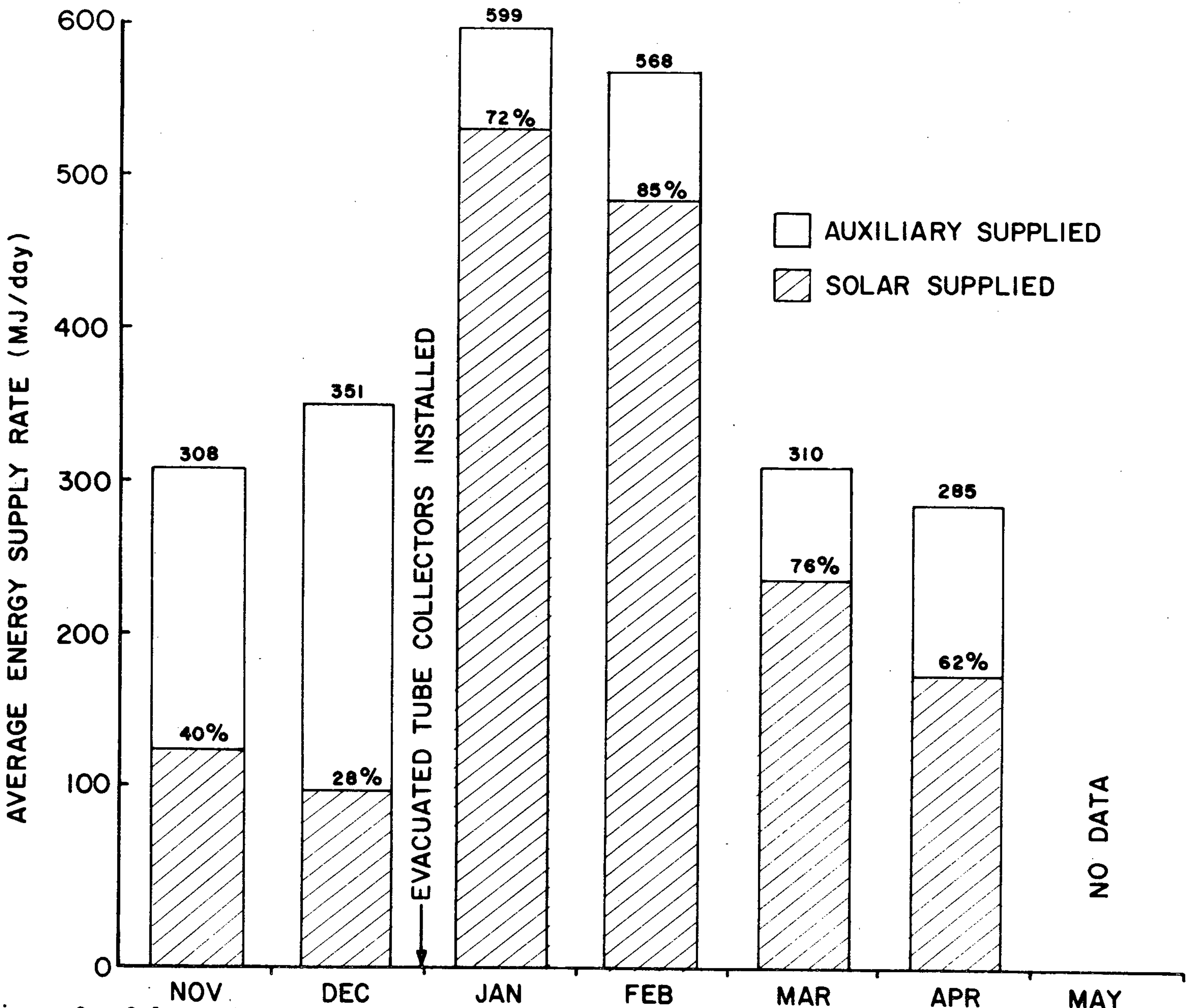


Figure 9. Solar and Auxiliary Contribution to Total Space and DHW Heating Load, Solar House I, 1976-77 Heating Season

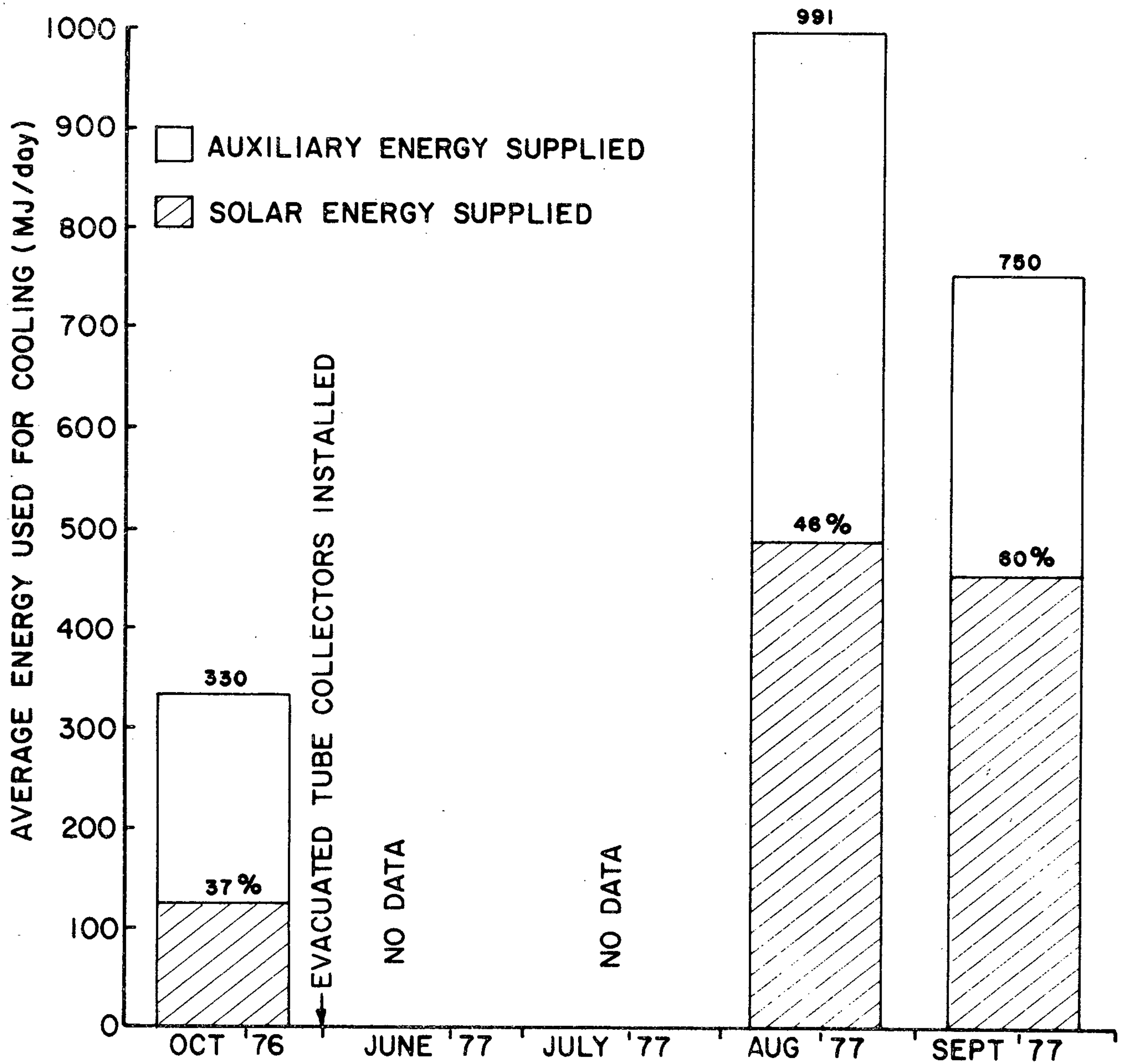


Figure 10. Solar and Auxiliary Contribution to Total Space and DHW Load, Solar House I, 1977 Cooling Season

Table 27

Monthly and Annual Energy Savings (MJ)

Month		Domestic Hot Water[1]	Space Heating	Space Cooling[2,3]		Totals	
		1	2	3	4	5	6
October	1976	1,544	84	- 1,469	2,835	159	4,463
November	1976	1,434	6,512	134	134	8,080	8,080
December	1976	2,101	4,970	0	0	7,071	7,071
January	1977	1,292	14,386	0	0	15,678	15,678
February	1977	1,302	15,730	0	0	17,032	17,032
March	1977	2,133	19,789	0	0	21,922	21,922
April	1977	3,731	6,755	0	0	10,486	10,486
May	1977	------------------------	------No	Data	Available-	--------	--------
June	1977	------------------------	------No	Data	Available-	--------	--------
July	1977	------------------------	------No	Data	Available-	--------	--------
August	1977	3,214	0	10,833	15,305	14,047	18,519
September	1977	1,578	0	11,446	15,528	13,024	17,106
Annual Totals		18,329	68,226	20,944	33,802	107,499	120,357

[1]Gas water heater has a measured combustion efficiency of 82 percent

[2]Gas boiler has a measured combustion efficiency of 77.7 percent

[3]Coefficient of performance of Arkla chiller for October and November was .48, and for August and September COP was .64

In summer operation, the energy savings in Column [3] are solar delivery to the cooling load less an approximation to the energy required for producing sufficient cooling to match (remove) the internal heat losses from the solar system (storage tank, DHW preheat tank, piping, valves, etc.). Column [4] shows the effects on the energy savings for cooling operations if it is assumed that the solar system heat losses did not contribute to the cooling load. For the month of November, the heat loss contribution to the cooling load is ignored since cooling took place for only part of one day. Sample calculations to obtain the values in Table 27 are shown below.

2.4.1. Sample Calculations -- Table 27

Column [1] -- The average heat losses from the DHW solar preheat tank (Q_{LPH}) were calculated to be 13.6 percent of the solar energy supplied (based on the average solar preheat tank temperatures and the experimentally determined heat loss rate for a particular temperature difference). The useful solar energy delivered to the DHW load (Q_{LPH}) is given by:

$$Q_u(DHW) = Q_{DHW} - Q_{LPH} = 0.864\ Q_{DHW}$$

where Q_{DHW} is the solar heat delivered to DHW load. The energy savings, E_{DHW}, listed in Column [1] of Table 27 is then $Q_u(DHW)$ divided by the auxiliary DHW unit's combustion efficiency (82 percent). Thus:

$$E_{DHW} = (\text{Column [1]}) = \frac{0.864 Q_{DHW}}{0.82} = 1.054\ Q_{DHW}$$

For January:

$$E_{DHW}(\text{Column [1]}) = 1.054(1226) = 1292\ \text{MJ}$$

Column [2] -- The energy savings for space heating, E_H, is the total useful energy delivered to the storage unit, Q_u, minus the monthly net energy gain in storage, G_{SG}, less the useful heat delivered to the DHW load, Q_u(DHW), divided by the gas boiler combustion efficiency, η_B. This is due to the fact that all heat losses from storage, piping, and the DHW system contribute to the solar space heating contribution.

For January (from Table 19 and the above calculation):

$$E_H = \frac{\bar{Q}_u - Q_{SG} - Q_u(DHW)}{\eta_B} = \frac{13{,}052 \text{ MJ} - 815 \text{ MJ} - 0.864\ (1{,}226 \text{ MJ})}{0.777}$$

$$E_H = 14{,}386 \text{ MJ}$$

Column [3] -- Q_{AIRS} is the amount of solar heat delivered to the cooling unit. However, the heat losses from the solar system add to the cooling load, and therefore must be accounted for in determining the net energy savings for space cooling, E_c. Therefore:

$$\eta_B E_c = Q_{AIRS} - (Q_{LS} + Q_{LPH})/COP$$

where

η_B	is the combustion efficiency of the gas boiler
Q_{LPH}	is the heat lost from the DHW solar preheat tank = 0.136 (Q_{DHW})
Q_{LS}	is the heat lost from storage
Q_{AIRS}	is the storage heat delivered to space cooling
COP	is the coefficient performance of the Arkla chiller = 0.64

For August (from Table 14):

$$E_c = \frac{Q_{AIRS} - (Q_{LS} + Q_{LPH})/COP}{\eta_B}$$

$$E_c = \frac{11,892 \text{ MJ} - [1799 + 0.136(3.125)]/0.64}{0.777}$$

$$E_c = 10,833 \text{ MJ}$$

Column [4] -- Assuming no solar heat losses contribute to the cooling load, we can obtain the energy savings for space cooling by:

$$E_c(\text{Column [4]}) = Q_{AIRS}/\eta_B$$

For August (from Table 14),

$$E_c(\text{Column [4]}) = 11,982 \text{ MJ}/0.777 = 15,305 \text{ MJ}$$

Column [5] -- Column [5] = Column [1] + Column [2] + Column [3]

Column [6] -- Column [6] = Column [1] + Column [2] + Column [4]

2.5 Energy and Mass Balance

Figures 7 and 8 show the typical solar system operation during the heating and cooling seasons, respectively. The curves indicated for both total solar and solar collected have dimensions of Megajoules per hour and are based on the average hourly values. All other heat quantities have the dimensions of Megajoules. During the heating season represented by Figure 7, the lowest useful temperature of the storage tank was 32°C and during the cooling season (Figure 8), the lowest useful storage tank temperature was 66°C. The cumulative storage energy is the energy contained in the storage tank above the useful temperature in each case.

3. System Economic Analysis

3.1 Collector and Installation Costs

The estimated cost of the Corning prototype evacuated tube collector is $35,000. As this is not a production model, this figure does not have much meaning. The Colorado State University installation is also not typical because it employs a separate test bed for the evacuated tube collector. However, the plumbing and methods of installation for evacuated tube collectors should eventually be similar to those for modular flat-plate collectors. The only difference would be the requirement for high temperature solder connections in the collector manifolds and in the connecting plumbing in the immediate vicinity due to the very high stagnation temperatures obtainable in the evacuated tube collector. This should entail only a slight additional expense.

3.2 Absorption Chiller System Costs

The Arkla Solaire WF-36 absorption chiller system estimated retail costs are itemized below:

Arkla Solaire WF-36	$4,200
Arkla Duct Coil 16-136	285
2 each, 300 gallon storage tanks	260
Cooling tower	600
Plumbing	500
Controls, including pumps and automatic valves	1,000
Total	$6,845

Arkla Industries is now marketing a complete solar space heating and cooling and domestic hot water heating system. The "ball park" price for this system for an "average" home is about $25,000, whereas it is in the vicinity of about $15,000 without the cooling for most commercial systems.

3.3 Operational Costs

Operational costs include the expense of natural gas for the auxiliary boiler and the hot water heater and electricity for powering pumps and blowers. Table 28 shows the total supplemental energy usage and associated cost during the period 1 October 1976 through 30 September 1977. It must be emphasized that there are a number of considerations which make the operational cost information for the CSU Solar House I System non-typical. The Corning collector is a prototype and will not be commercially available. System design considerations were oriented toward matching the characteristics of the previous flat-plate system and not toward cost-effectiveness. Also the donated pumps were not the most efficient available.

3.4 Maintenance Frequency and Costs

The Corning evacuated tube collector units required no maintenance. The new Arkla absorption chiller lost vacuum apparently during shipping and had to be pumped down. The previous unit also lost some vacuum during the winter months and required pumping down at the beginning of each cooling season. Considerable time and effort were expended in developing the controls and the instrumentation. The control system, finalized in September, is believed to be quite reliable. However more operating

Table 28

Supplemental Energy Costs

Energy Source and Use	Usage	Cost
Auxiliary energy (natural gas)		
Space heating		
Space cooling		
Domestic hot water	3271.6 m^3 (115,536 ft^3)	$204.15
Electrical energy		
Pumps		
Blowers	10,135 kw-hr	$405.40
Total		$609.55

Based on a cost of $0.0624 per cubic meter gas and $0.04 per kw-hr electricity

experience will be required to develop more definite estimates of maintenance frequency and costs. The cooling system controls are quite complex because cold storage is included and this experimental mode has not yet been adequately tested. The chiller/cooling tower/duct coil system and its associated pumps are controlled by a conventional controller that is supplied with the chiller and is reasonably reliable. One electro-mechanical relay in this system failed and was replaced during the 1977 cooling season.

4. Solar Collectors

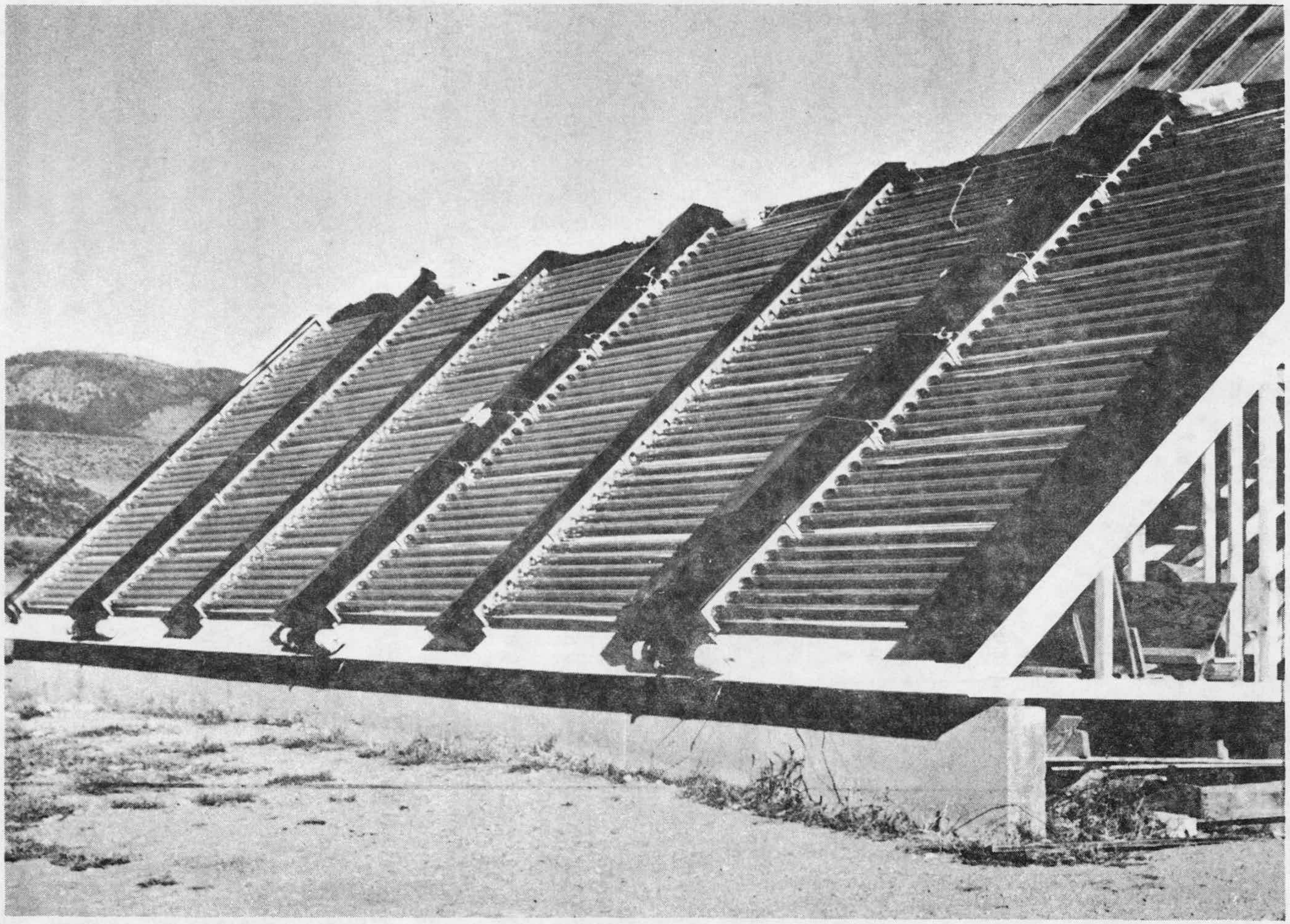
4.1 Description of the Physical Configuration

4.1.1. Corning Evacuated Tube Collector

The Corning evacuated tube collectors at CSU Solar House I are shown in Photograph 4. The pyrex glass tubes are 2.4 mm thick (0.095 in), 10.2 cm (4 in) in diameter, approximately 2.25 meters (7.5 ft) in length, and contain .186 square meters (2 sq ft) of absorber plate. The ratio of roof area covered by the collectors (less manifolds) to the absorber area is 1.46. The smallest collection unit which can be installed consists of a module of six collector tubes connected in series. All modules are then connected in parallel flow. The design flow rate through each module is approximately 100 liters/hour (.45 gpm). Figure 11 shows the detail of the Corning collector.

The absorber plate is made of 0.81 millimeter (0.032 in) thick copper. The exposed surface is plated with a "black chrome" selective surface; the back side was not treated. The absorber plate was welded to a 7.1 millimeter (0.280 inch) outside diameter U-shaped copper tube which carries the coolant fluid. The absorber structure is supported by equally spaced metal clips resting on the glass tube along its length.

The entrance and exit of the coolant tube at one end is required for differing thermal expansion of the glass and metal in the longitudinal direction. The rate of thermal expansion of the copper is much higher than that of glass. Furthermore, the absorber plate experiences a daily thermal cycle of typically 100°C, while the glass tube remains only a few degrees above ambient.



Photograph 4. Corning Evacuated Tube Collectors

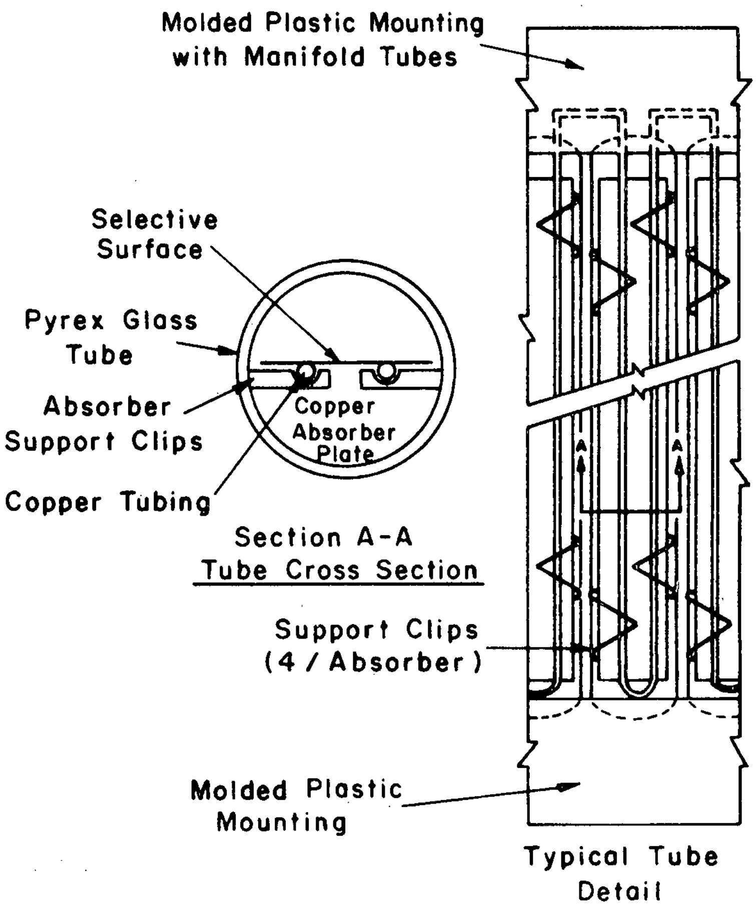


Figure 11. Corning Evacuated Tube Collector Detail

Before hermetically sealing, each tube is evacuated to 0.013 PA (10^{-4} mm Hg). A barium oxide material is deposited inside one end of each tube to "scavenge" any remaining gas particles. Vacuum failure can easily be detected by visual inspection of this material.

4.2 Thermal Performance Characteristics

4.2.1. Collector Efficiency

Experimental measurements on a single evacuated tube collector have been performed by Corning in a solar simulator with normal incidence of the beam radiation and no wind. Results of these tests were normalized to the parameter $(T_{in}-T_{amb})/I_T$, as shown in Figure 12. A least squares linear fit was found. The resulting model for performance of a single collector tube at normal solar incidence of beam radiation is:

$$\text{Efficiency} = .788 - .517\ (T_{in}-T_{amb})/I_T\ [°Cm^2/w] \qquad [1]$$

$$\text{Efficiency} = .788 - .295\ (T_{in}-T_{amb})/I_T\ [Hr\text{-}°F\text{-}Ft^2/Btu]$$

4.2.2. Pressure Drop Through Collectors

The pressure drop across a 12 module array of the 3 array system was measured using the 50 percent by weight antifreeze solution at 32.2°C and at 93.3°C. For a flow rate of 15.14 liters per minute the pressure drops are 28.3 kPA (4.1 psi) and 34.5 kPA (5.0 psi) at these two temperatures. With the centrifugal pump used the system operates at a constant pressure drop allowing the volumetric flow rate to increase as the collector fluid temperature increases.

4.2.3. Optical Efficiency versus Incident Angle

Research indicated that evacuated tube collector performance is affected by non-normal sun angles and by interactive effects with

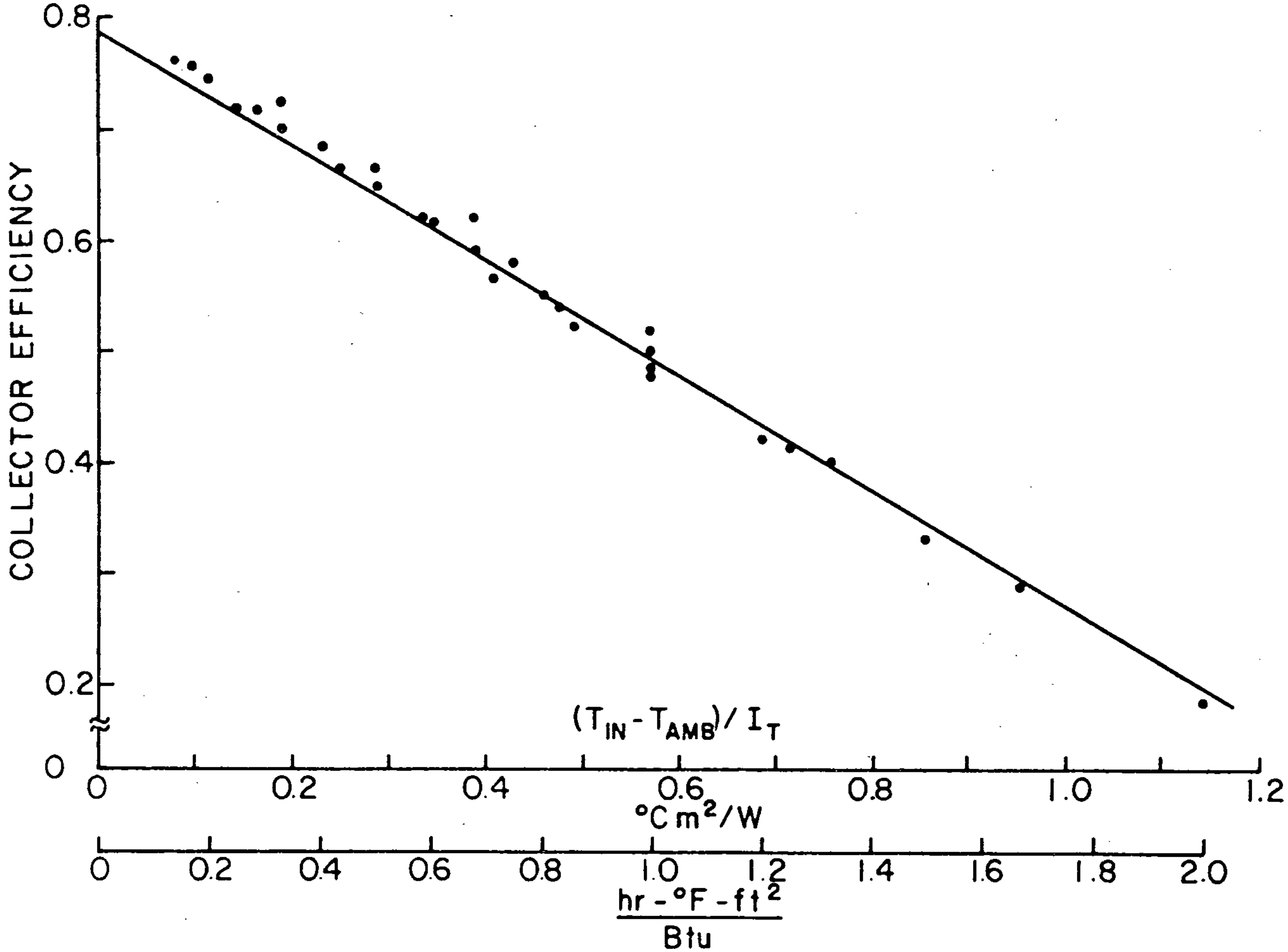


Figure 12. Normalized Collector Simulator Test Performance

adajcent tubes, none of which are accounted for in the above model. These effects include changes in the transmissivity of the glass tube, internal reflections in the tube, reflections from adjacent tubes, shading by adjacent tubes, and reflections from the surface behind the collector tubes. All of these phenomena cause the effective $(\tau\alpha)$ product of the collector to vary with sun angle. The sun angle FACTOR is given in Table 29. This factor is the combined result of all these effects for beam radiation on the $(\tau\alpha)$ product as a function of the angles ψ and ϕ which are defined in Figure 13. The effective $(\tau\alpha)$ product for diffuse radiation has been calculated to be 0.774.

To correctly account for these factors, the I_T term in Equation [1] should be replaced with:

$$I_T = \text{FACTOR}\ (I_{beam}) + 0.774\ (I_{diffuse}) \qquad [2]$$

4.2.4. Thermal Loss Coefficient

Thermal loss coefficient as a function of the difference between the ambient and collector fluid inlet for no wind conditions was determined experimentally to be: $U_L = 0.517\ w/m^2 - °C\ (0.295\ Btu/Hr\text{-}°F\text{-}Ft^2)$, where the area is based on the absorber plate dimensions and the temperature difference is the average fluid inlet temperature minus ambient temperature.

4.3 Lifetime Performance Characteristics

4.3.1. Corrosion and Working Fluid Stability

The wetted parts within the collector are all copper. In order to reduce internal corrosion, the heat transfer fluid design velocity should be less than one meter per second. The Corning collector design velocity is about 0.75 meter per second.

Table 29

Corning Evacuated Tube Collector Sun Angle FACTOR

± ψ \ ± θ	20°	30°	40°	50°	60°	70°	80°	90°
0°	.741	.890	.956	.981	.998	.995	.995	1.00*
10°	.755	.901	.959	.998	1.00	1.00	1.01	1.01
20°	.760	.907	.967	1.00	1.01	1.01	1.01	1.02
30°	.793	.931	.989	1.03	1.04	1.03	1.03	1.05
40°	.807	.951	1.01	1.04	1.06	1.05	1.05	1.05
50°	.726	.788	.849	.886	.894	.901	.903	.903
60°	.525	.641	.726	.782	.797	.817	.880	.880
70°	.212	.390	.512	.647	.639	.666	.676	.676

* Normal Incidence

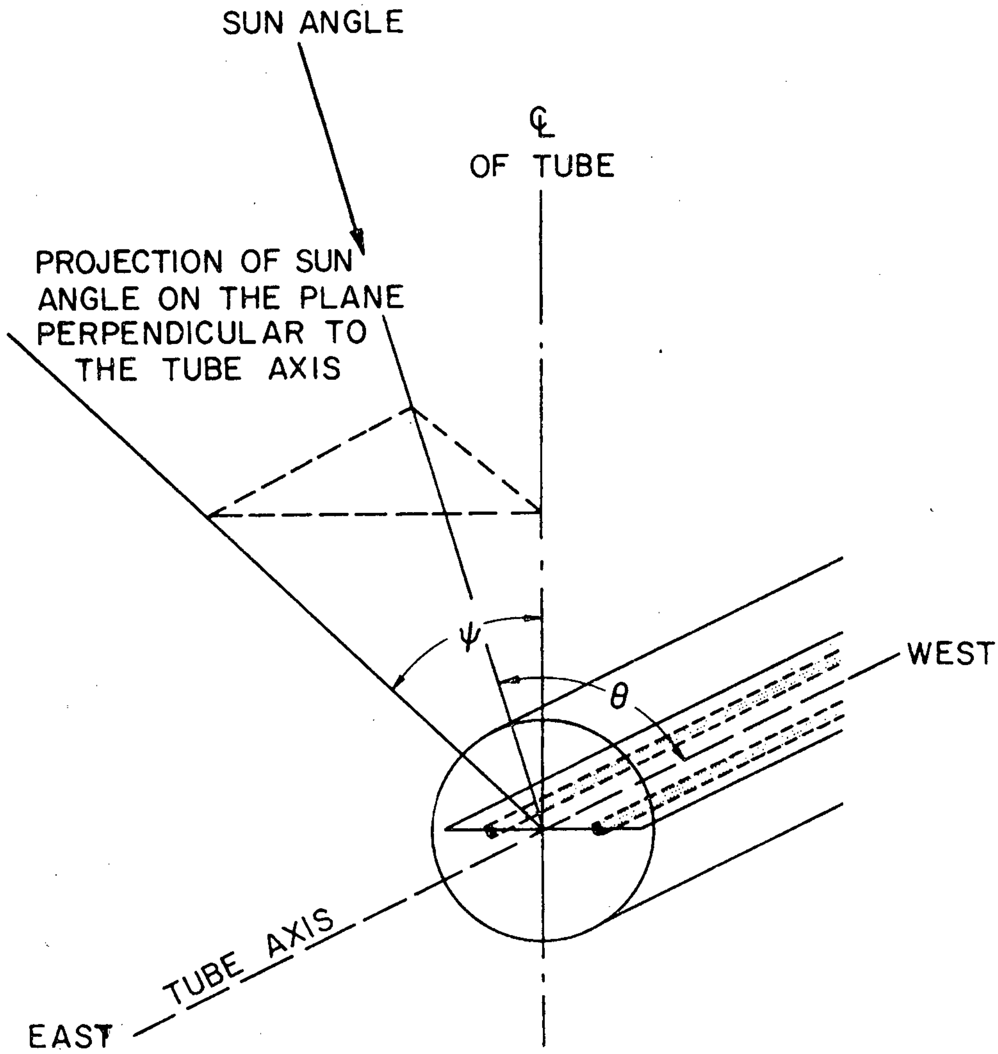


Figure 13. Collector Sun Angles

The 50/50 ethylene glycol (antifreeze) and water mixture provides freeze protection down to -37°C (-34°F) and contains additives to prevent corrosion. However, two potential problems are created by the high stagnation temperatures obtainable with this collector. If the collector is permitted to boil dry, non-volatile products would be deposited in the coolant passages. This could result in degraded performance from increased heat transfer resistance and higher pumping costs from restricted coolant passages.

A second high temperature problem is caused by the possible degradation of the coolant fluid. Above 150°C (300°F) the ethylene glycol partially decomposes into an acid that can chemically attack the copper tubing. The fluid pH was frequently checked and the problem was never encountered.

To prevent deposition of solids within the collectors, all of the liquid passing through the collector loop is continuously filtered. The filter cartridges used remove particules as small as 50 microns. This filter has a pressure drop of 14.5 kPA (at a flow rate of the ethylene glycol-water mixture of 60.5 liters/minute and at a temperature of 96°C). The pressure drop across the filter appears to vary inversely with the diameter of the smallest particle size removed.

The filter cartridge was replaced after the first week of operation to remove any construction residue. Thereafter, the filter cartridge was replaced whenever the measured system flow rate was reduced below about 90 percent of design flow rate. This only occurred after the collector was drained and refilled.

4.3.2. Leakage

There has been no apparent leakage of the collector heat transfer fluid from the collector array or system components. Minor leakage has occurred around some performance monitoring instruments which are frequently removed for calibration or maintenance. Make-up fluid for these leaks is provided automatically by the three expansion tanks. The tanks are filled manually as required (about every two months).

4.3.3. Hot Spots

Prevention of hot spots is accomplished by good flow distribution through the collector array. Quantitatively uniform flow is accomplished by ensuring that the head loss due to friction across each solar collector module (ΔH) is significantly greater than the total head loss in either manifold (Δh), hot or cold, i.e., the ratio of $\Delta h/\Delta H$ should be small (<0.1).

The design value of $\Delta h/\Delta H$ for the Corning solar collector array is approximately 0.03 for a flow rate of one liter per second (16 gallons per minute) of water at a temperature of 95°C (203°F). The value of $\Delta h/\Delta H$ for a 50 percent ethylene glycol solution is less at the same temperature because Δh will increase less than ΔH. Calculations show that the flow in the middle collector section will be approximately 99 percent of the flow in the two end sections.

Experimental efforts show that the measured flow distribution in the Corning solar collector array is quite uniform, with deviations of less than one percent among the three subarrays. When the average outlet temperature for each section is 94°C, the greatest variation of the observed collector outlet temperature is ± 0.3°C (0.5°F), indicating equal flow distribution in all collector modules.

4.3.4. Breakage

Glass breakage during the installation of the collector involved only one tube out of a total of 216 installed. No breakage has

5. Heat Transfer Subsystem

5.1 Description of Physical Configuration

5.1.1. Working Fluids

Fluids in the heat transfer subsystem are an ethylene-glycol/water solution in the collector loop and water (with corrosion inhibitor) in the thermal storage unit, and heat exchangers (see section on Thermal Energy Storage Subsystem). In the collector loop the heat transfer liquid is an aqueous solution of 50 percent ethylene glycol by weight.

5.1.2. Circulating Pumps

The circulating pumps are all centrifugal type with cast iron pump casing and brass impellers. With the exception of the evacuated tube collector pump, which operates at 3450 rpm, all pumps operate at 1750 rpm and are configured in line with the electric motor with a spring type flexible coupling. The hot water preheat and cooling tower pumps are "off-the-shelf" units. The other pumps in the system were adapted to specific pressure drop (head) versus flow rate requirements. This was accomplished by using pumps slightly larger than needed and reducing (trimming) impeller diameters to obtain the exact specifications.

5.1.3. Heat Exchangers

For liquid-liquid heat exchange without mixing of the liquids, shell-and-tube heat exchangers, commercially constructed with copper and brass, were selected. A single-pass counterflow design is used. The single-pass counterflow arrangement allows the temperature difference between fluids to be nearly constant along the exchanger. The collector heat exchanger is made up of two units in series because a single unit of sufficient length was unavailable.

The single-pass design involves multiple parallel tubes and a relatively high pumping rate to develop turbulent flow in the tubes. On the storage side of the collector heat exchanger, a flow rate of 95 liters per minute (25 gpm) is obtainable with modest pump power (1/6 horsepower) because resistance in that loop is low. The high flow rate does, however, nearly eliminate temperature stratification in the storage tank. Highly stratified storage temperatures would thus come at the cost of a larger exchanger or a greater temperature difference.

5.1.4. Air Duct Coils

Solar heating requires a larger air duct coil surface than does auxiliary boiler heating. The increased size is due to the lower temperatures from solar storage, a 38°C to 65°C design temperature, compared with the boiler water at 90°C. The commercial coil (Arkla DCH 36-90) consists of copper tubes with aluminum fins housed in a 50 by 55 cm (20 by 22 inch) duct section. For air conditioning an even larger duct coil (Arkla DCH 60-136) was required because of the very low latent cooling load due to the dry climate. It is the same type and construction as the heating coil but is housed in a 57 by 72 cm (22½ by 28 inch) duct section.

5.2 Thermal Performance Characteristics

5.2.1. Heat Exchanger Performance

The heat exchangers as well as the plumbing are wrapped with insulation to reduce heat losses in the heat transfer subsystem. The operating parameters and performance characteristics are listed in Table 30.

Table 30

CSU Solar House I Heat Exchanger Operating Parameters

Heat Exchanger	Shell			Tube			Design Heat Rate Kw	UA w/°C
	Flow ℓ/sec	Temp. Drop °C	Pressure Drop kPa	Flow ℓ/sec	Temp. Drop °C	Pressure Drop kPa		
Collector	1	10.0	62	1.6	5.1	1.4	33.85	6594
Hot Water	1	10.9	1.7	0.13	10.9	1.7	5.86	528

The operating point for the Corning collector pump is one liter per second (16 gpm) at 18.3 meters (60 ft) of water head. This was accomplished by trimming the impeller on a 3450 rpm centrifugal pump powered by a 1.12 kW (1.5 h.p.) electric motor. It should be noted that this project was only concerned with thermal performance of the system and no attempt was made to minimize pump power required. Readily available pumps were generously donated by Bell and Gossett and modified for our application, hence many overpowered pumps are used. The storage heat exchanger pump operating point is 1.6 liters per second (25 gpm) at 2.13 meters (7 ft) of head and is accomplished with a 1750 rpm centrifugal pump powered by a 125 watt electric motor. The domestic hot water heat exchanger pump operates at 0.13 liters per second (2 gpm) at 0.6 meters (2 ft) of head and is powered by a 18.6 watt, 1750 rpm magnetically coupled centrifugal pump.

5.2.2. Air Duct Coil Performance

The operating parameters and performance characteristics for the heating and cooling duct coils are listed in Table 31. The house air circulation is accomplished by a belt-driven squirrel cage blower

Table 31

CSU Solar House I Air Duct Coil Operating Parameters

Duct Coil	Water Flow ℓ/sec	Water Temp. Change °C	Air Flow Rate ℓ/sec	Air Temp. Change °C	Design Heat Rate Kw	Water Pressure Drop kPa	Air Pressure Drop Pa
Heating	0.547	5.6	2543	37.5	20.5	71.7	34.9
Cooling	0.394	5.6	2543	11	11.4 sensible 2.4 latent	99.6	25

(powered by a 1725 rpm, 373 watt (1/2 h.p.) electric motor. The hot water is delivered to the heating coil or the Arkla chiller generator by a 1750 rpm, 250 watt (1/3 h.p.) centrifugal pump. The chilled water is delivered to the cooling coil by a similar pump of the same size.

6. Thermal Energy Storage Subsystem

6.1 Description of Physical Configuration

The thermal energy storage system consists of 4275 liters of water in a steel tank. The storage tank was fabricated from 16 gauge (1.5 mm) galvanized sheet steel. Seams and pipe connections to the tank are arc welded. A 60 cm (24 inch) diameter manhole at the top of the tank allows complete access to the inside. Each piping connection on the tank is provided with a shut-off valve and a neoprene hose connection to the copper piping. The tank is electrically isolated from all other plumbing components to prevent electrolytic corrosion of the tank.

The specifications of the storage tank are:

Diameter	1.67 meters	(5.5 feet)
Height	1.82 meters	(6.0 feet)
Height of top cone section	.27 meters	(0.9 feet)
Volume	4275 liters	(1131 U.S. gallons)
Weight empty	213 kilograms	(470 pounds)
Weight filled	4374 kilograms	(9644 pounds)

6.2 Corrosion Control

The composition of the corrosion inhibitor used is given in Table 32. When added to distilled and/or demineralized water, the resulting pH of the aqueous solution is between 7.5 and 8.0.

Insulation on the storage tank consists of 15.2 cm (6 inches) of sprayed on cellulose insulation ($R = 17.14\ °Cm^2/w$). Measured heat loss greatly exceeded this specified rating, probably because of dampness of the insulation.

Table 32

Composition of Corrosion Inhibitor

Ingredient	Percent by Weight
Mercaptobenzothiazole (technical grade, 92 percent min)	15.1
Sodium borate decahydrate, $Na_2B_4O_7 \cdot 10H_2O$)	75.7
Disodium phosphate anhydrous $Na_2H\ PO_4$	9.2
	100.0

7. Air Conditioning Subsystem

7.1 Description of Physical Configuration

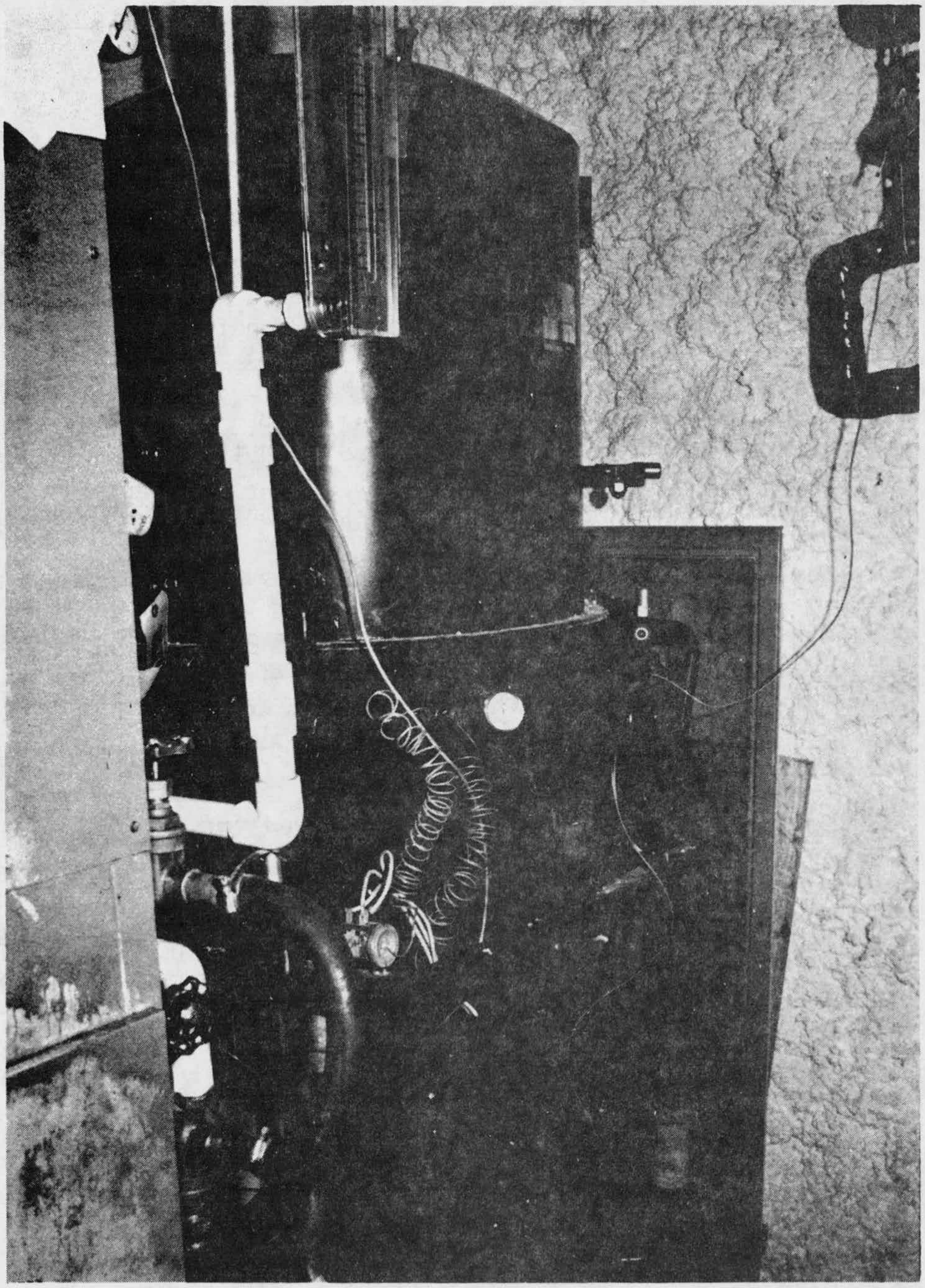
The cooling subsystem selected for CSU Solar House I is an Arkla Solaire Model WF-36 shown in Photograph 5. This lithium bromide absorption water chiller utilizes hot water from solar storage or the auxiliary boiler as the heat supply to the generator. This unit is nominally rated at 10.5 kW (3 tons, 38 MJ/hr). The lithium bromide in the refrigerant solution was modified from the normal 52 percent to approximately 50 percent. This is a result of the much lower condenser water temperatures that are available in this arid region. This change also reduces the minimum allowable hot water generator temperature from 77°C to 66°C (170°F to 150°F).

7.1.1. Heat Rejection Method

A forced draft cooling tower is employed for cooling the water circulated through the condenser and absorber of the air conditioner. In order to match the capacity of the Arkla air conditioner the cooling tower must have a capacity of about 23.4 kW (95 MJ/hr, 90,000 Btu/hr) with a 6°C (10°F) approach to the ambient wet bulb temperature and a 10°C (18°F) range.

The unit chosen is a galvanized steel, asbestos-packed cooling tower with a nominal capacity of 28 kW (101.3 MJ/hr, 96,000 Btu/hr). The air fan is driven by a 0.24 kW (1/3 horsepower) electric motor. The tower is designed for water flow rates of 1.0 to 1.7 ℓ/sec (16 to 27 gpm).

A Penn Aquastat electric fan control permits operation of the cooling tower fan only when required for a preset discharge water



Photograph 5. Arkla Solaire WF-36 Absorption Chiller

temperature. There are two conditions, both of which must be met, for the fan to operate. First, the Arkla unit must be running, and second, the water temperature from the tower must be at least 24°C (75°F).

With a 0.76 ℓ/sec (12 gpm) of condensing water at 24°C (75°F), a hot water supply of 42.4 ℓ/min (11.2 gpm) at 84°C (183°F) and chiller water flow of 27.3 ℓ/min (7.2 gpm) at 7.2°C (45°F), the chiller will provide 12.13 kW (43.7 MJ/hr, 41,380 Btu/hr) of cooling at a thermal coefficient of performance of 0.556. The additional capacity above the three-ton rating is due to the modified charge and lower temperature condenser water.

7.2 Thermal Performance Characteristics

The steady-state performance, i.e., capacity and coefficient of performance, is a function of the generator and condenser water temperatures. Characteristics performance of the Arkla chiller with the modified charge system for arid climates is shown in Figure 14. Data for these characteristic performance curves was generated at Arkla Industries and Colorado State University by operation of the chiller at steady-state conditions.

The minimum operating temperature for the generator is 66°C (150°F). Below the limit, the unit can experience crystallization problems. The location of the Colorado State University Solar Houses at 1585 meters (5200 ft) elevation puts an upper limit of 95°C (203°F) on hot water temperature (local boiling point) because a non-pressurized solar storage system is used. The coefficient of performance characteristics of the modified charge Arkla chiller shown in Figure 14 shows a decrease in coefficient performance when generator water reaches temperatures

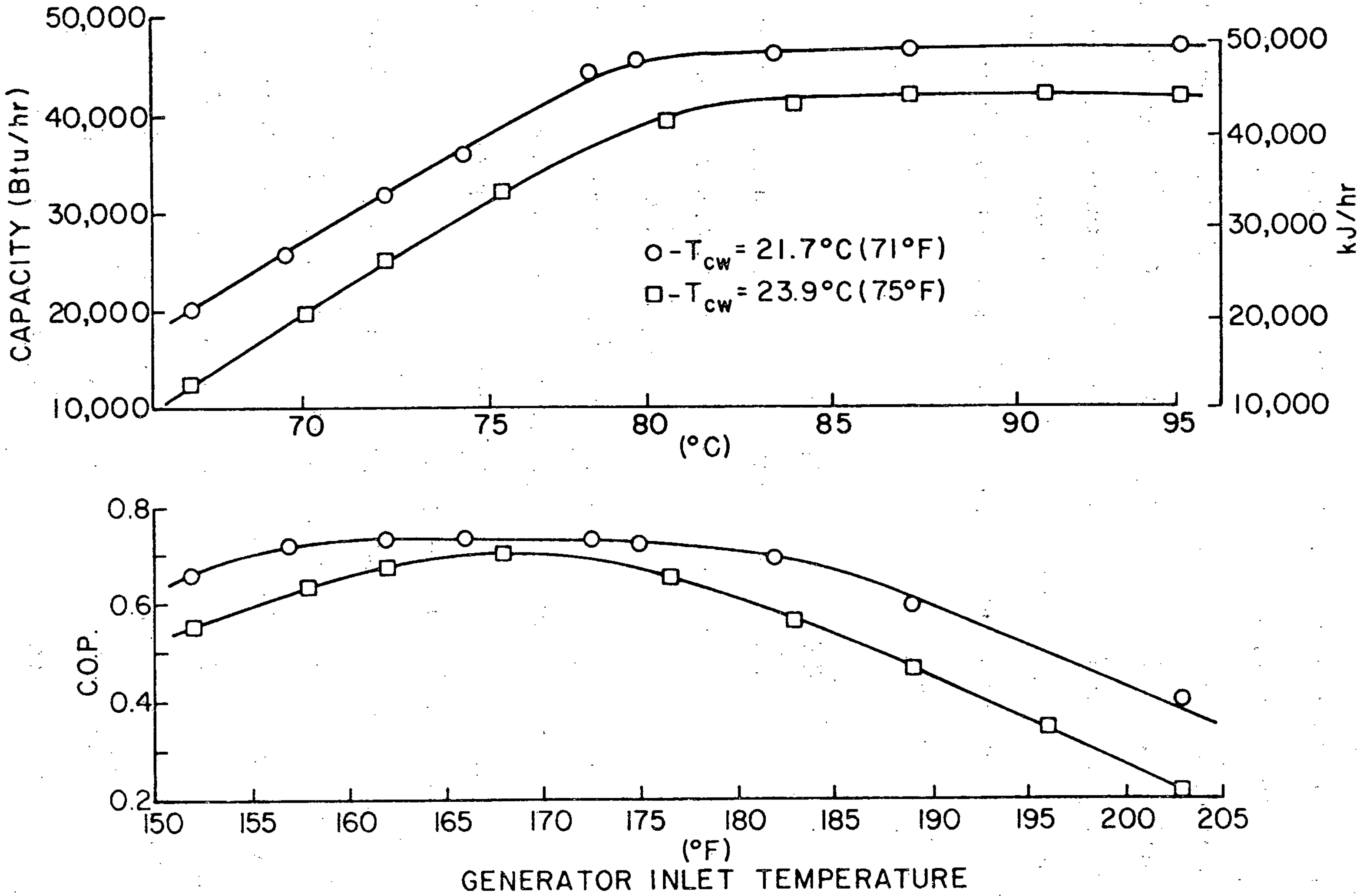


Figure 14. Modified Charge Arkla Chiller Performance Characteristics

over 76.7°C (170°F). Operation above this temperature causes stored solar energy to be wasted with a corresponding decrease in the seasonal solar contribution to the cooling system. By using a tempering valve, as shown in Figure 15 water returning from the generator can be mixed with high temperature solar heated water to supply the generator with water not exceeding 82°C (180°F). This temperature was chosen because it is the minimum chiller generator temperature which will provide the maximum cooling capacity of the machine.

Subsequent experimentation and analysis indicated that the modest performance improvement did not justify the additional expense. The primary reason is that the "over-fired" condition generally occurred during spring and fall, when the incident beam radiation was essentially normal to the collector. These days required only marginal cooling capacity, so the lower COP did not reduce the seasonal solar fraction.

A secondary reason for removing the tempering valve is the design match among the collector size, the cooling machine, and the house's cooling requirements. The chiller capacity closely matches the daily cooling demand. Also, the chiller's hot water requirements closely approximate the average production rate of the Corning collectors.

Operation of an absorption chiller requires many heat exchange processes at various temperature levels within the chiller. When a chiller first becomes operational, the fluids and heat exchanger surfaces approach their normal operating temperature but, until steady-state conditions are achieved, cooling capacity is reduced. When a chiller is turned off, the fluids and material temperatures decay approximately exponentially to the ambient temperature of the chiller unit. Therefore, the performance of an absorption chiller in a transient state depends on how long the unit has been off as well as how long it has been on.

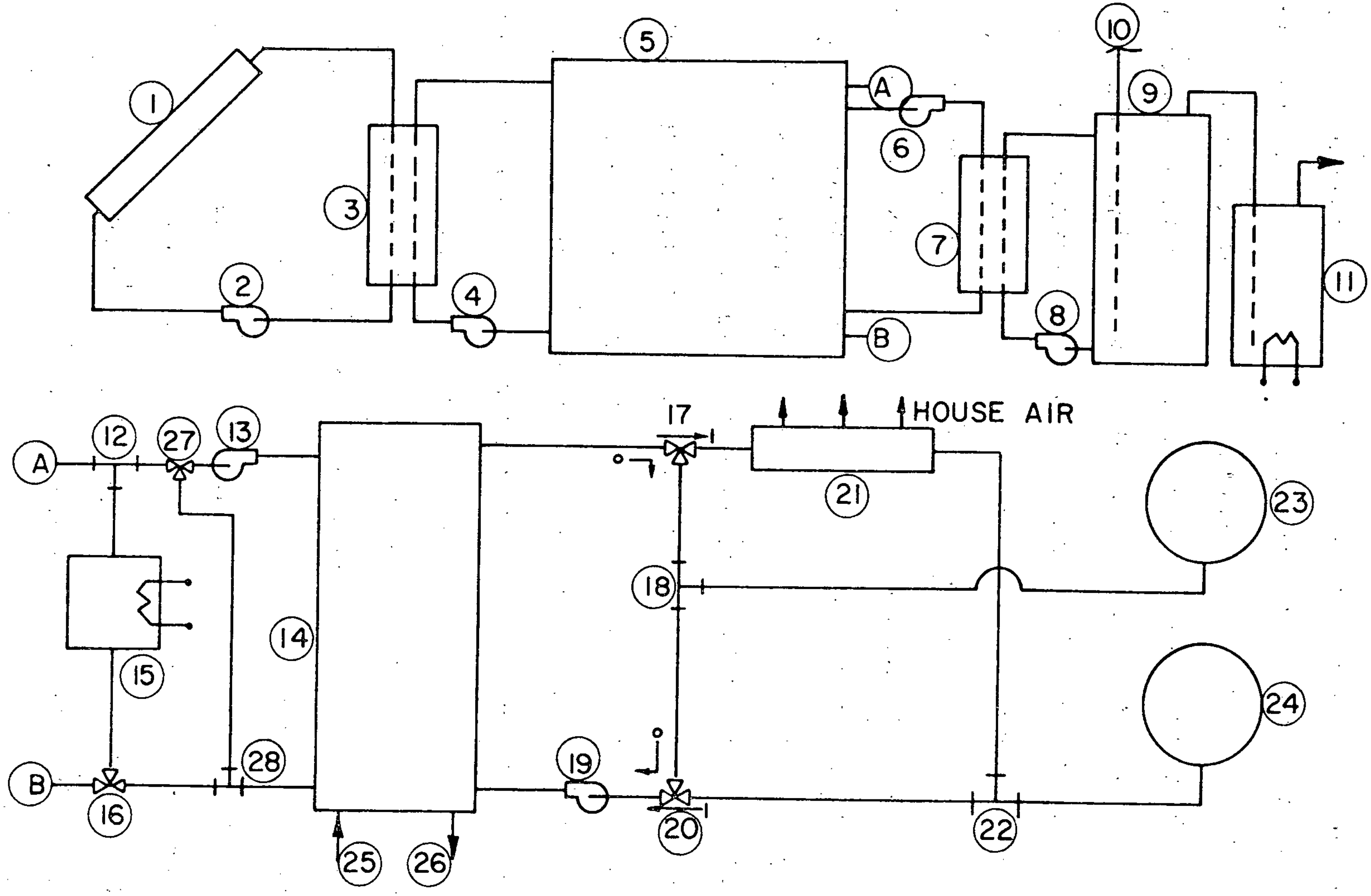


Figure 15. Solar Cooling System with Chilled Water Storage Components Identified in Table 33

Table 33

Solar System Component Descriptions

Component Number	Description
1	Corning evacuated tube collectors
2	Collector fluid (antifreeze solution) pump
3	Collector/storage heat exchanger
4	Collector/storage heat exchanger pump
5	Heat storage tank (water)
6	Solar hot water preheat heat exchanger pump (shell side)
7	Solar hot water preheat heat exchanger
8	Solar hot water preheat heat exchanger pump (tube side)
9	Solar hot water preheat tank
10	Potable water supply
11	Auxiliary fueled hot water heater
12	Tee
13	Arkla generator pump
14	Arkla 3 ton lithium bromide chiller
15	Auxiliary boiler for Arkla generator
16	Three-way control valve
17	Three-way control valve *
18	Tee
19	Chilled water pump
20	Three-way control valve *
21	Duct heat exchange coil (chilled water/house air)
22	Tee
23	"Cool" storage
24	"Warm" storage
25	Condenser water flow from cooling tower
26	Condenser water flow to cooling tower
27	Tempering valve (used only in arid climates)
28	Tee (used only in arid climates

* Operational Mode	Control Valve Position	
	17	20
Chilling directly to load	1	1
Cold storage to load	1	0 (chiller off)
Chilling to cold storage	0	1

Transient reponse experiments with the modified charge Arkla unit were performed at CSU with "off" times between chiller operation of one-half two and eight hours. The results are shown in Figure 16. Observation of the experimental data reveal that transient characteristics do not exist for more than thirty minutes after start-up and that during this transient period, at least 50 percent of the steady-state cooling capacity of the chiller is delivered to the load.

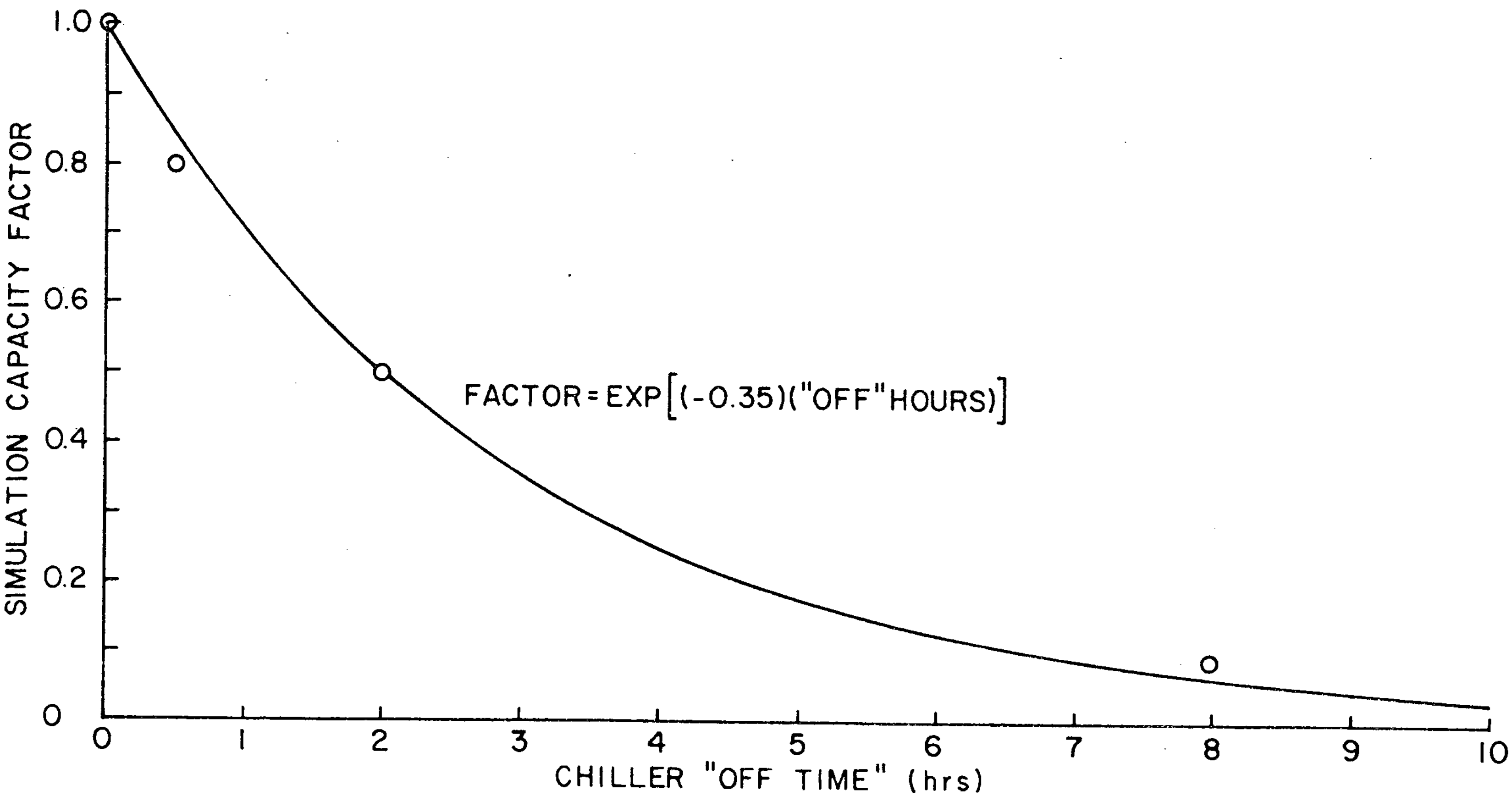


Figure 16. Chilled Transient Response Characteristics

occurred in over one year of operation. The vacuum in one tube was lost at or shortly after start-up, but no detectable system performance degradation resulted.

8. Conclusions

The data in this report provide a basis for concluding that the new ARKLA Solaire WT-36 water chiller in combination with evacuated tubular collectors constitute a viable heating, cooling and hot water system for buildings. Solar fractions of heating and cooling were not as large as they might have been due to loads that were abnormally high compared to a residential occupancy of such a building. The higher loads were due to a greater occupancy rate of the house, more frequent and prolonged opening of doors and windows, presence of heat generating research equipment and high losses from the thermal storage tank. Supporting simulation studies and examination of the detailed hourly data have established that substantially higher solar heating and cooling fractions would have been achieved with a residential usage. A factor arguing against the use of an absorption cooling system for a residence, but not for a commercial building, is the potential need for sophisticated system maintenance attention.

Some additional conclusions that are not directly discernible from the data presented in this report, but which can be made with the aid of the supporting simulation study and the detailed hour by hour data, concern the viability of cool storage and the location of the hot water heat exchanger. The addition of cool storage increases the solar fraction by reducing the extent of transient chiller operation and slightly reducing the average thermal storage tank temperature. However, the improvement in performance is not sufficient to offset the cost of cool storage. The relocation of the hot water heat exchanger from the thermal storage tank to the collector loop improves the solar cooling fraction. However, the reduced solar hot water fraction more than offsets the savings. Therefore, the total solar fraction is higher with the heat exchanger returned to its original location.

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