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MASTER

PERFORMANCE OF RESIDENTIAL SOLAR HEATING AND COOLING SYSTEM WITH FLAT-PLATE AND EVACUATED TUBULAR COLLECTORS:
CSU SOLAR HOUSE I

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I. General Description of System Project and Environment

A. Objective of Project

Measurements in Solar House I at Colorado State University have provided comparison data on space heating, water heating, and cooling by systems in which flat-plate collectors and evacuated tube collectors were used. Data were procured on 47 days during operation of the flat-plate collector and on 112 days when the house was heated or cooled by the evacuated tube collector system.

The primary objectives of the project are the development of a functional and efficient solar heating and cooling system and the comparison of its performance with that obtained with the previous system and with other solar systems being developed at CSU. Design of an effective control system became an important supporting objective of the project.

It was concluded that the system comprising an evacuated tubular collector, lithium bromide absorption water chiller, and associated equipment is highly effective in providing space heating and cooling to a small building, that it can supply up to twice the space heating and several times the cooling obtainable from an equal occupied area of good quality flat-plate collectors, and that a greater fraction of the domestic hot water can be obtained by supplying its heat from main storage. The cost-effectiveness of the system, in comparison with one employing a good flat-plate collector, can be determined when commercial pricing data are made available.

B. Description of the Environment

Solar House I is located on the Colorado State University (CSU) Foothills Research Campus at the western edge of the city of Fort Collins, Colorado. The location is 40.6 north latitude and 105.1 west longitude and is at an altitude of 1585 meters. Between August 1974 and November 1976, a solar energy supply system

comprising a site-built flat-plate liquid collector, hot water storage, a lithium bromide air conditioner, and a gas-fired boiler were used for heating and cooling the building and for its hot water supply [1,2]. In December 1976, an evacuated tube collector supplied by the Corning Glass Works and a new lithium bromide absorption water chiller supplied by Arkla Industries were installed and connected to the other heating and cooling system components. The performance of this new system has been measured since 1 January 1977.

C. Description of System

The heating and cooling system in CSU Solar House I as operated during the period of this investigation is shown in Figs. 1 and 2, and a list of components identified by number in Fig. 2 is presented in Table 1. In October and November 1976, the flat-plate collector on the house roof was used, and in the following months, the Corning evacuated tube collector on an adjacent sloped platform was used.

The house is heated by air from a heat exchanger supplied with solar heated water from the thermal storage tank or from an auxiliary boiler. Cooling requirements are met by use of cold water circulated from the Arkla chiller or from cool storage. Heat energy is supplied to the chiller by hot water either from thermal storage or the auxiliary boiler. Heat rejection from the chiller is to water circulated through a cooling tower outside the building. Service hot water is heated by exchange with the hot collector fluid and stored in an 80-gallon tank followed by a conventional gas-fired water heater. Heat is transferred to the main storage by circulating a non-freezing solution of ethylene glycol through the collector and through an exchanger in which water from storage is heated.

The building is designed as a residence but is used as a laboratory and office space. The conditioned space is 128.4 sq m on the main floor and a full heated basement. It has a heat demand of 17.5 kW at 41.3°C temperature difference.

The Corning collector consists of 216 pyrex tubes 102 mm diameter, 2.25 m long, and 2.4 mm thick; they are evacuated to 0.013 Pa (10^{-4} mm Hg). The absorbers in the tubes are 0.8 mm copper plates with a black chrome selective surface and a total area of 39.9 sq m. The area of sloping surface occupied by the collectors is 75.2 sq m, comparable to the flat-plate occupied area of 71.3 sq m. Freeze protection is by a 50-50 mixture of ethylene glycol and water. Normal maximum operating temperature is about 110°C. The $F_R\tau\alpha$ product is 0.788 and the U_L factor is 1.675 watt per sq m, degree C. The collector is oriented due south at a 45 degree slope.

Thermal storage is in 4277 liters of corrosion-inhibited water in a galvanized vertical cylinder. Heat exchange from the collectors is by a tube and shell counterflow heat exchanger. The tank, located in an insulated basement room, is itself somewhat poorly insulated with a heat loss coefficient of 0.78 watt per sq m, degree C.

Cool storage is 1130 liters of water contained in two 1130 liter polypropylene tanks. For cooling the building, chilled water from the colder tank is circulated through the cooling coil in the

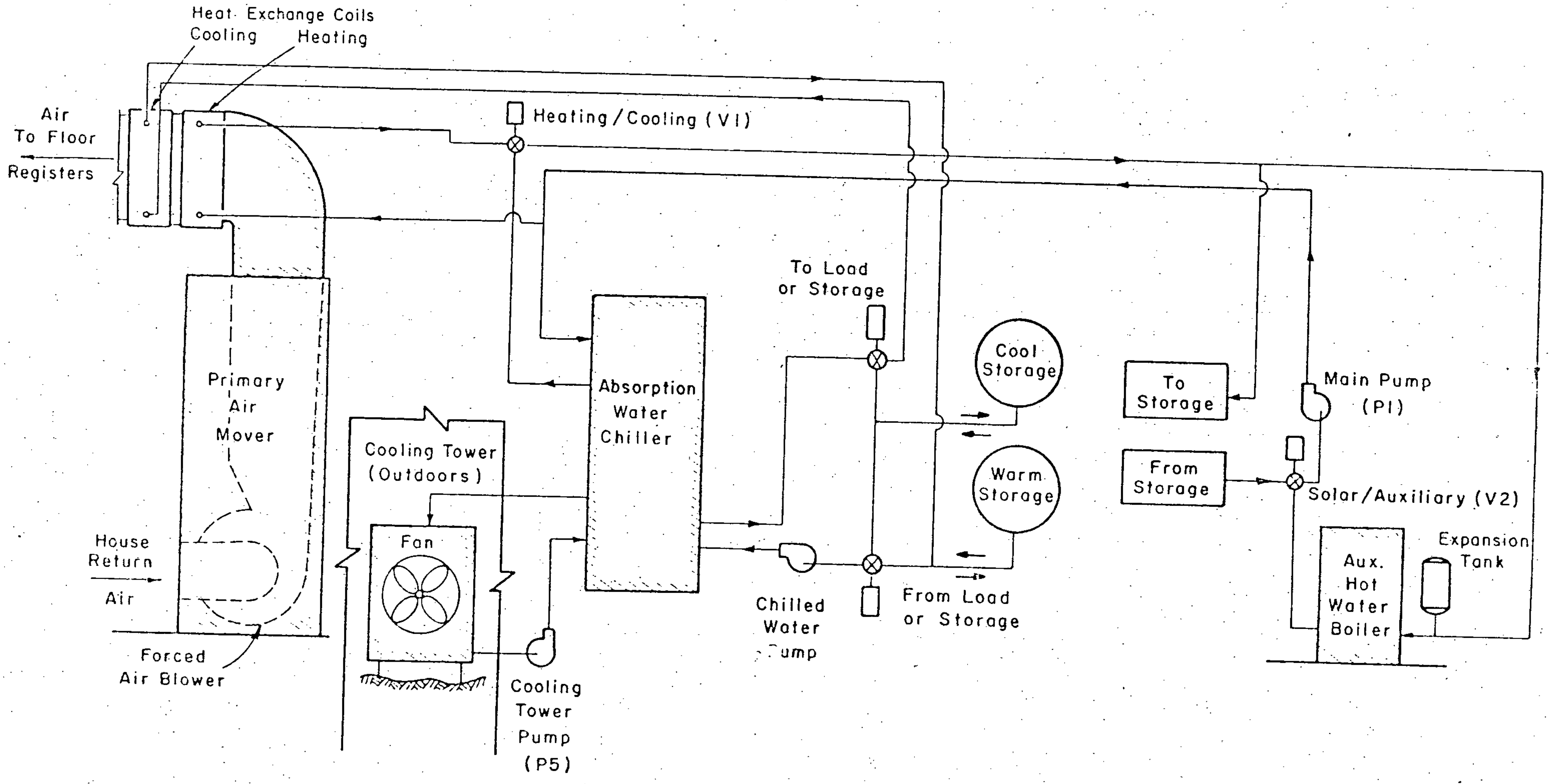


Fig. 1: Solar House I Heating - Air Conditioning - Hot Water Equipment

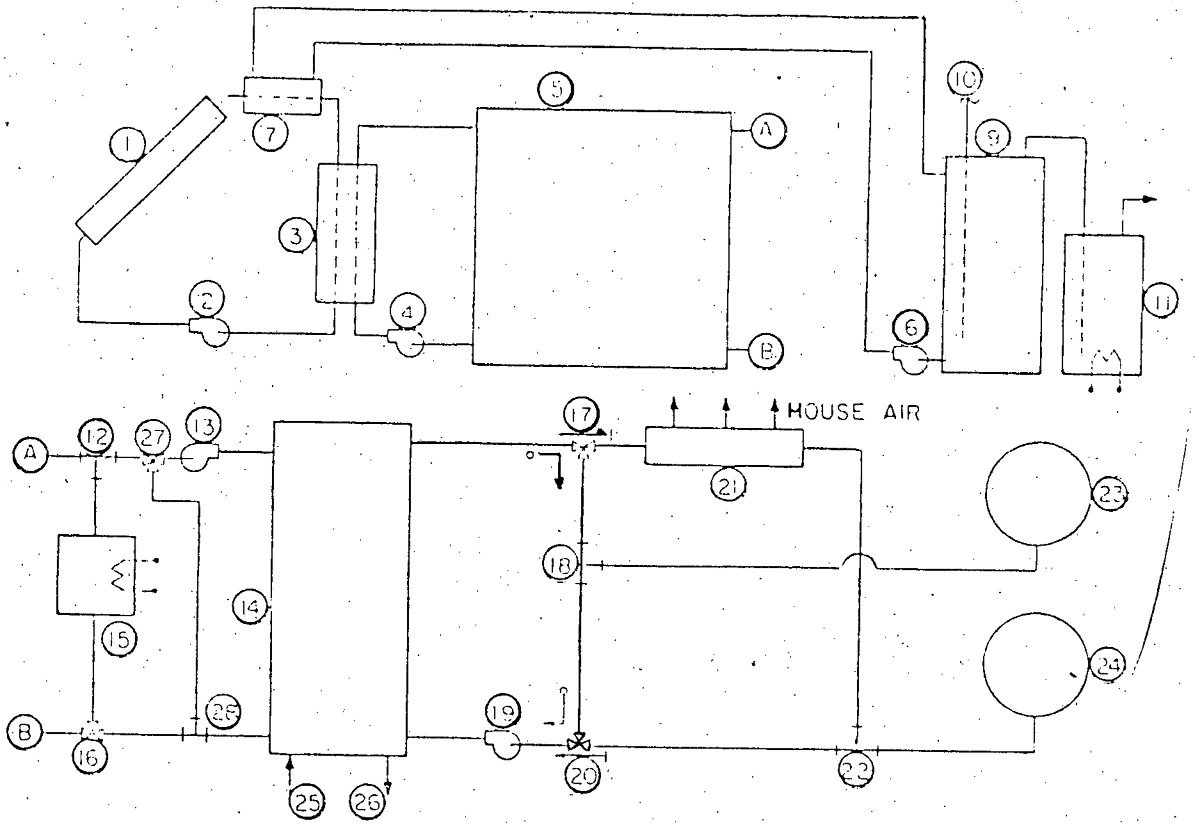


Fig. 2: Solar Cooling System with Chilled Water Storage Components Identified in Table 1

Table 1: 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
9	Solar hot water preheat tank
10	Potable water supply
11	Auxiliary fueled hot water heater
12	Tee
13	Chiller generator pump
14	Arkla 3-ton lithium bromide chiller
15	Auxiliary boiler
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

Table 1 operating modes

Operational Mode	Control Valve Position	
	17	20
Chilling directly to load	1	1
Cold storage to load	1	0
Chilling to cold storage	0	1

forced air system to the warmer tank of the pair. This water is then recooled by circulating it from the warmer tank through the chiller evaporator coil, and back to the colder tank. These operations are diagrammed in Fig. 3.

Auxiliary energy for heating, cooling, and hot water is natural gas. The boiler for heating and cooling has a rated capacity of about 85 MJ/hr at the 1585 m altitude and 77% boiler efficiency under ideal conditions.

The cooling unit is an Arkla Solaire WF-36 absorption water chiller with a charge modified from 52% to 50% LiBr to better match cooling water temperatures usually prevailing at this location. In the commercial version, the chiller has a design point of 38 MJ/hr at typical cooling water temperatures of 29°C (85°F). The CSU chiller has a capacity of about 50 MJ/hr at a COP of almost 0.8, and it can be operated at generator temperatures as low as 66°C with a corresponding capacity of 20 MJ/hr.

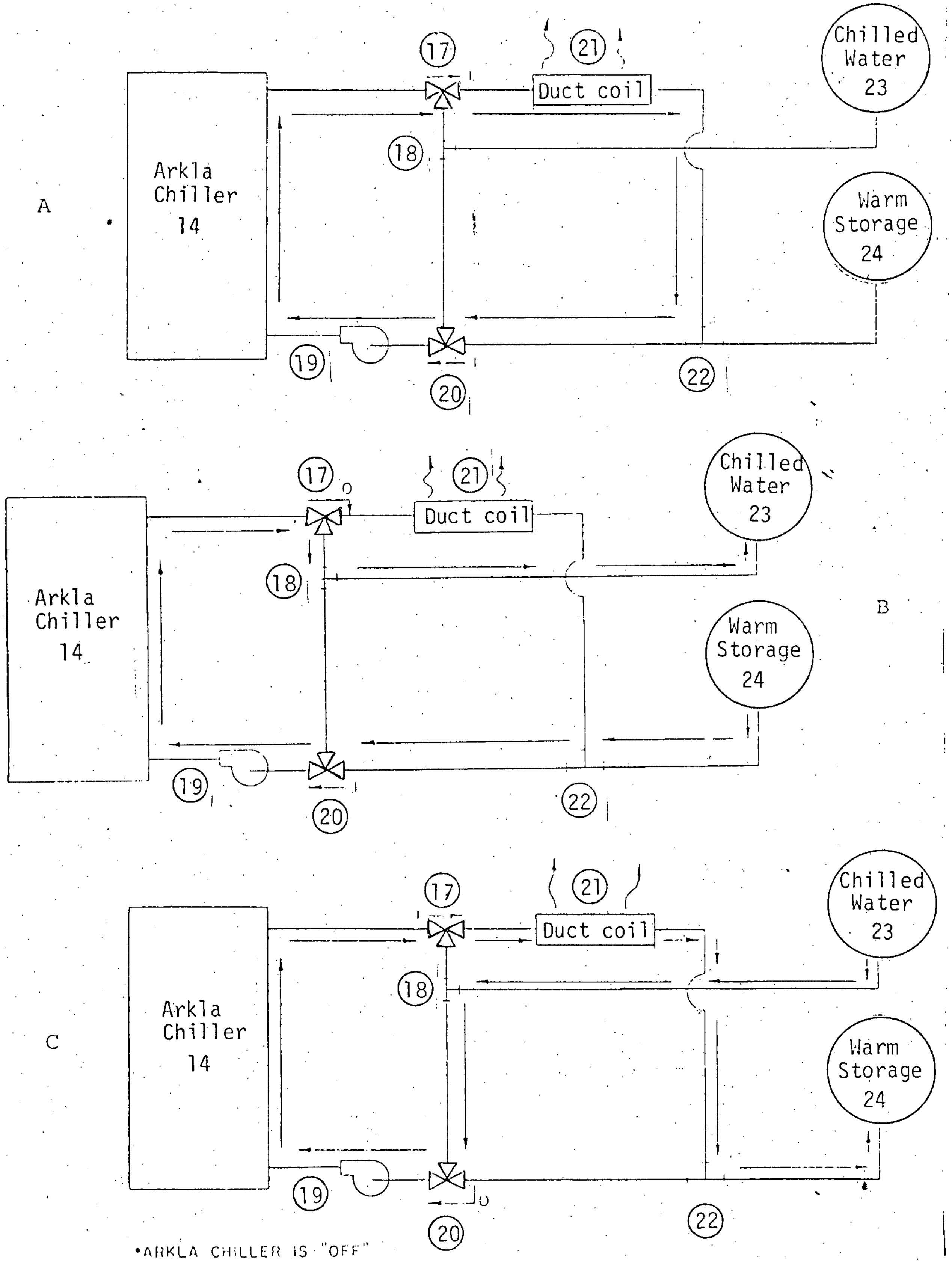
To provide a typical residential hot water demand, 75 liters are automatically discharged at 7:00, 13:00 and 20:00 hours each day. There is additional uncontrolled hot water usage by the occupants. A 300 liter preheat tank is interfaced with the collector loop by means of a tube and shell counterflow heat exchanger. Preheated water flows from the preheat tank to a conventional natural gas-fired 150 liter hot water tank and heated further, when necessary.

II. System Thermal Performance

A summary of monthly and annual energy use for space heating, domestic hot water (DHW) heating, and space cooling is presented in Table 2 and Figs. 4 and 5. The collector performance is presented in Fig. 6. The first two months of data were obtained with the system employing flat-plate collectors, whereas heating and cooling during the following nine months were supplied by the evacuated tube collector system.

A. Data Quality

Data quality and consistency were monitored by periodic checking of individual flow and temperature measurements against each other and by daily and monthly heat balances on the system. In Table 3, the figures in the first column should equal the totals of the next five columns. Differences are due to fluctuation in heat stored at month ends, unknown and unmeasured losses, experimental errors, and occasional boiling in the storage tank. The month-to-month agreement is seen to be imperfect, but longer term totals are considered sufficiently consistent for reliable conclusions. The large percentage deviation in March and April is due largely to considerable boiling in the storage tank.



•ARKLA CHILLER IS "OFF"

Fig. 3: Chilled Water Storage Operational Modes
A. Direct Cooling by Chiller
B. Cooling to Chilled Water Storage
C. Cooling from Chilled Water Storage

	Total Solar *	Solar to Storage **	Solar to Load	Solar to Heating	Aux. Heating	Solar to Hot Water	Aux. to Hot Water
Oct '76	1404	191	183	65	0	47	61
Nov '76	1086	159	174	124	113	46	60
Dec '76							
Jan '77	1087	415	396	360	110	36	52
Feb '77	1149	360	379	338	37	41	60
Mar '77	1394	566	285	229	12	57	41
Apr '77	852	297	227	108	20	119	84
May '77	-	-	-	-	-	-	-
Jun '77	-	-	-	-	-	-	-
Jul '77	-	-	-	-	-	-	-
Aug '77	1287	439	417	0	0	73	47
Sep '77	1584	537	452	0	0	50	38
FPC	1248	175	179	94	56	47	61
ETC	1227	436	359	259§	45§	63	54

	Solar to Cooling	Aux. to Cooling	Solar Frac. Heating	Solar Frac. Cooling	Solar Frac. Heat & Cool	Data Base Days	Solar Frac. Hot Water
Oct '76	71	64	1.00	0.53	0.68	28	0.44
Nov '76	4	0	0.52	1.00	0.53	19	0.43
Dec '76							
Jan '77	0	0	0.77	-	0.77	20	0.40
Feb '77	0	0	0.90	-	0.90	12	0.41
Mar '77	0	0	0.95	-	0.95	29	0.58
Apr '77	0	0	0.86	-	0.86	21	0.63
May '77	-	-	-	-	-	0	-
Jun '77	-	-	-	-	-	0	-
Jul '77	-	-	-	-	-	0	-
Aug '77	344	459	-	0.43	0.43	13	0.61
Sep '77	402	236	-	0.63	0.63	17	0.57
FPC	38	32	0.63	0.54	0.60	24	0.43
ETC	373†	348†	0.85	0.52	0.67	19	0.54

*Based on 75.2 m^2 gross collector area and 39.9 m^2 absorber area for Jan-Sep and 71.3 m^2 gross collector area and 67 m^2 absorber area for Oct-Nov

**Solar to storage does not include solar to hot water load

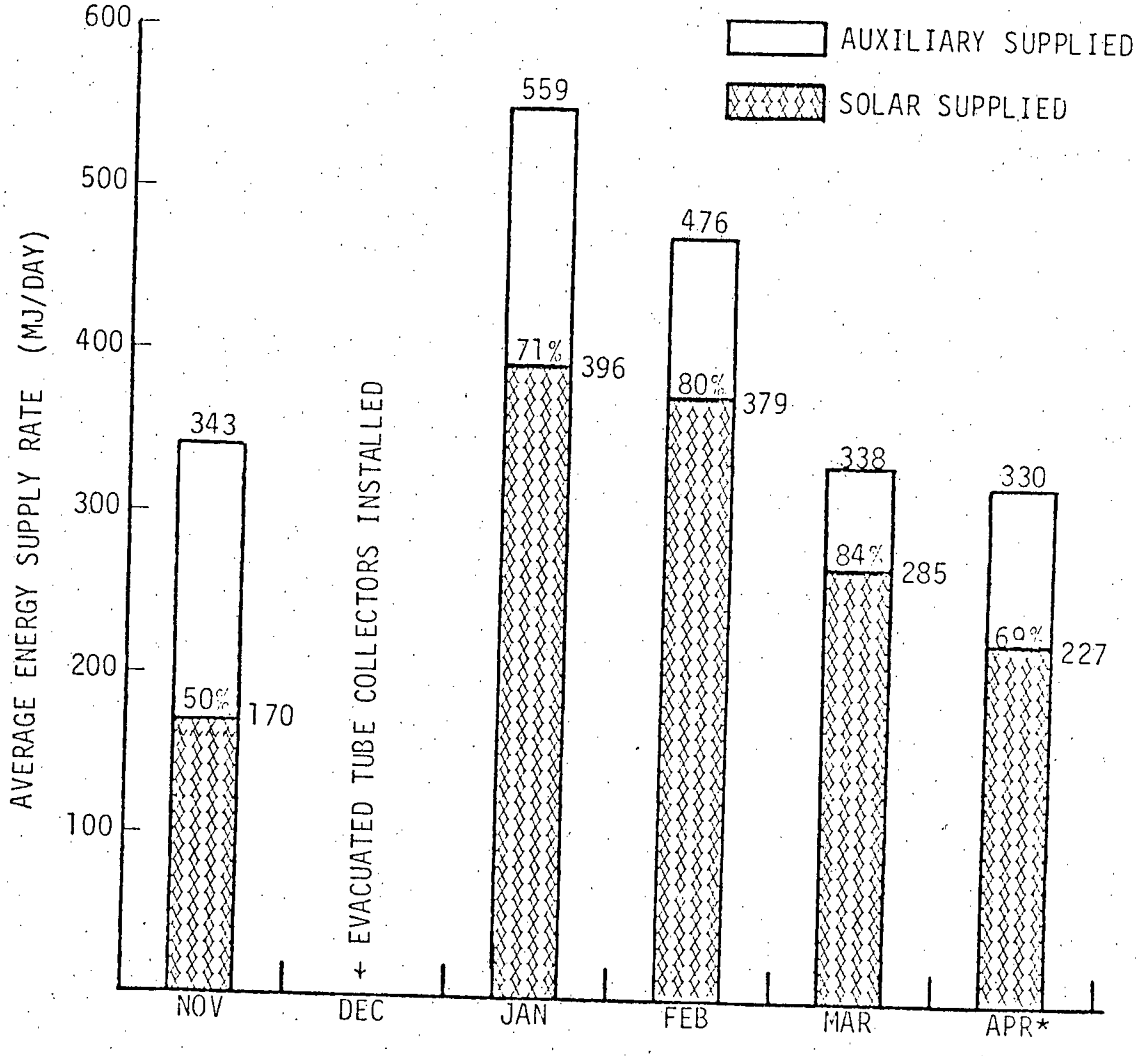
FPC = Flat Plate Collector average, Oct-Nov 1976

ETC = Evacuated Tubular Collector average, Jan-Sep 1977

§ Averages for four winter months only

† Averages for two summer months only

Table 2. Monthly and Annual Averages of Daily Energy Quantities, MJ/day, and Fractions



*Note reduced collector area for part of April

Fig. 4: Solar and Auxiliary Contribution to Total Space Heating and DHW Heating, Solar House I, 1976-1977 Heating Season

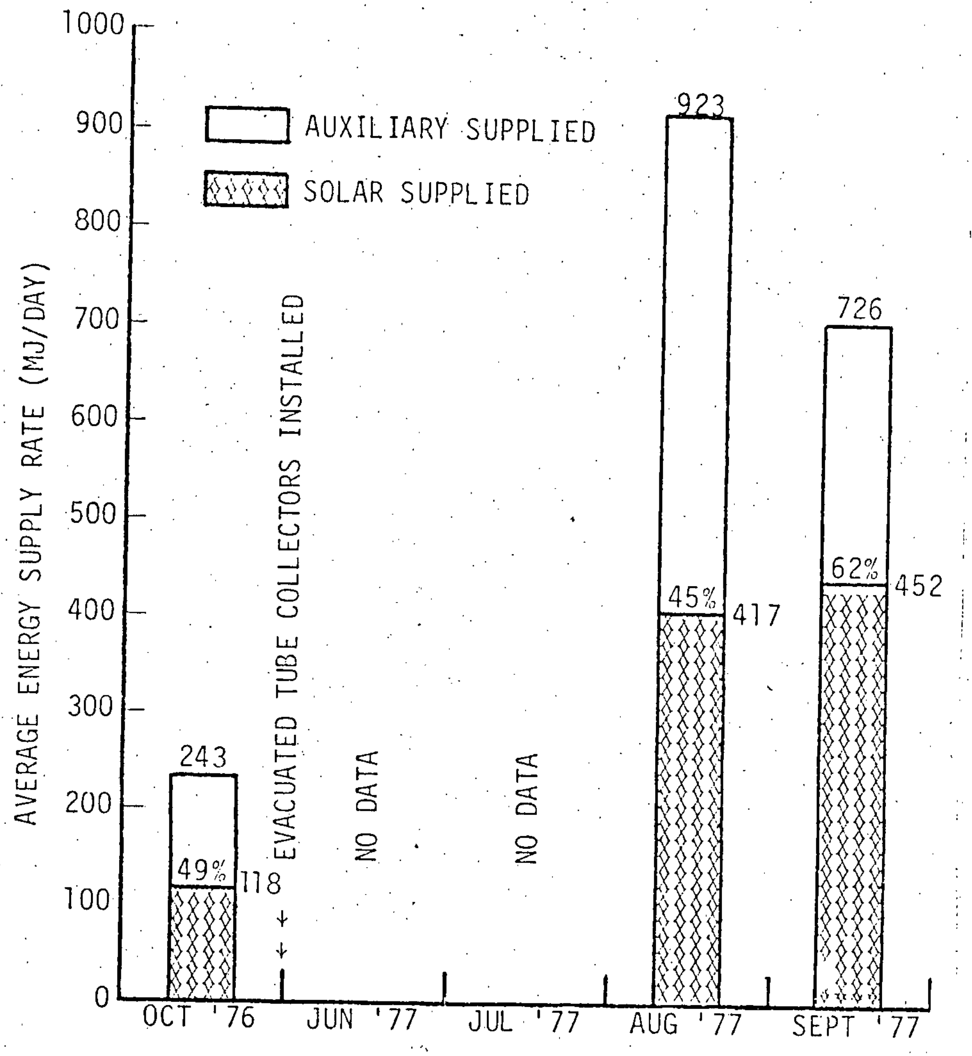
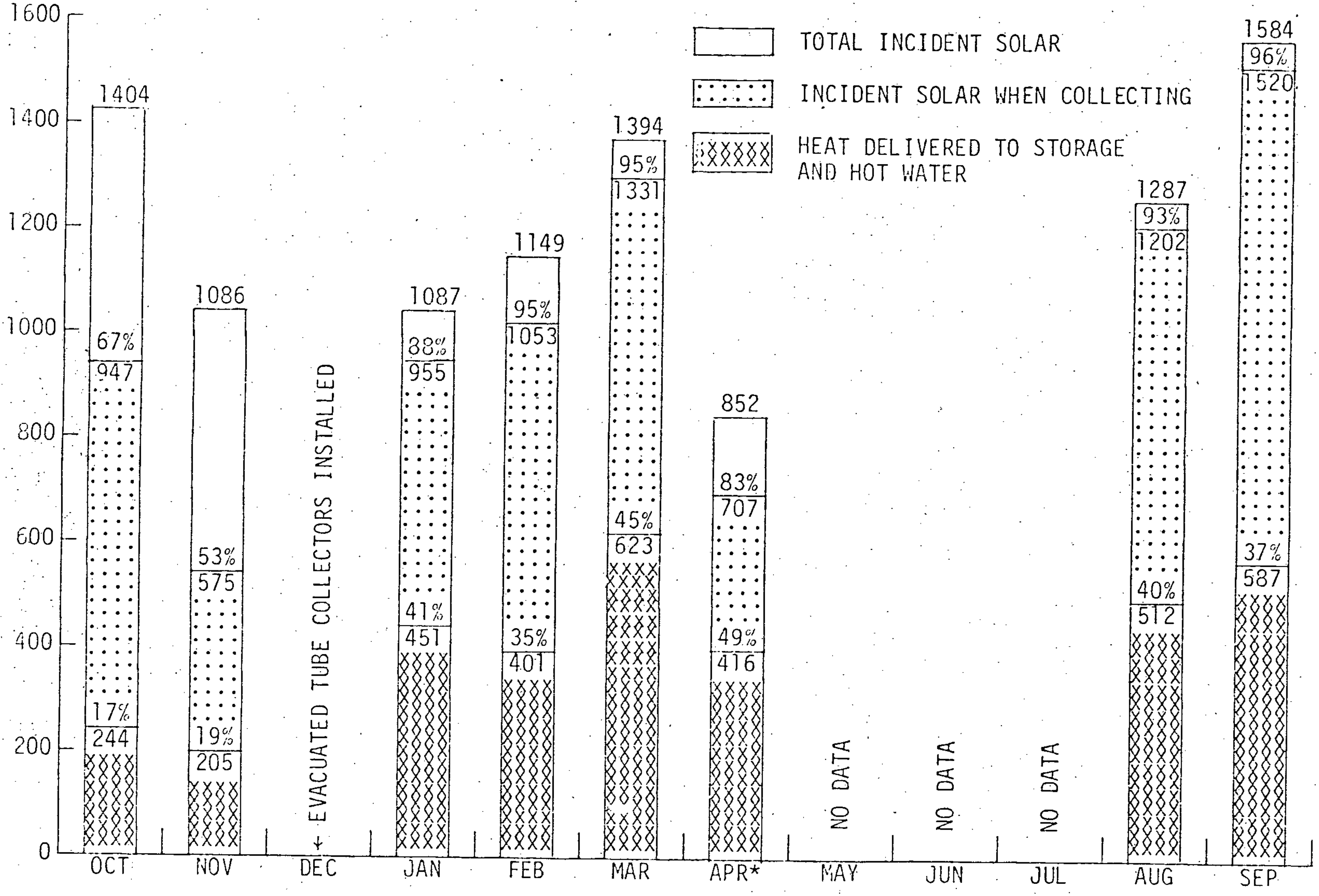


Fig. 5: Solar and Auxiliary Contribution to Space Cooling and Hot Water Heating, Solar House I, 1976-1977 Cooling Season



* Collector area reduced during April

** Based on 71.3 m^2 flat-plate collector area and 75.2 m^2 evacuated tube collector area

Fig. 6: Collector Performance

	(1) Apparent Energy to Storage, MJ	(2) Energy Lost From Storage, MJ	(3) Net Storage Energy Gain, MJ	(4) Energy to Heating Coil, MJ
Oct	6,122	1,941	299	72
Nov	4,772	1,093	-858	2,643
Dec				
Jan	12,861	1,003	988	10,176
Feb	10,090	1,168	-111	8,298
Mar	17,553	1,908	348	5,176
Apr	8,902	1,494	127	1,740
May				
Jun				
Jul				
Aug	13,603	1,784	- 19	0
Sep	16,642	1,826	30	0

	(5) Energy to Chiller MJ	(6) Energy to Service Hot Water, MJ	(7) Balance MJ *	(8) Percent Deviation **
Oct	2,203	1,465	-142	- 1.17
Nov	104	1,375	415	3.84
Dec				
Jan	0	1,107	-403	- 1.58
Feb	0	1,150	-415	- 1.99
Mar	0	1,759	8,362	31.30
Apr	0	3,574	1,967	12.40
May				
Jun				
Jul				
Aug	10,676	2,254	1,162	4.46
Sep	12,065	1,497	1,224	3.82

* Balance = (1)-(2)-(3)-(4)-(5)-(6)

** Percent Deviation =
(7)/(1)+(2)+|(3)|+(4)+(5)+(6)

Table 3: Monthly Solar Energy Balances

Only two months of data on the present system with flat-plate collectors are available. Data in the preceding winter and summer were obtained before the system was provided with cold water storage, water heating in collector loop, and improved control features [2]. Solar collection and solar space heating are unusually low in November. In previous years, a similar (but not identical) system with the same collector provided more than 90% of the space heating in November [2], rather than the 52% supplied in 1976. This difference is largely accounted for by unusually severe weather conditions November 12-14 and November 27-30, 1976. Daily results [3] show unusually high heat demands (for this time of year) and no collectible solar energy in the first period, and extremely cold weather and poor solar conditions in the second period. Only a small fraction of the heating load during those eight days was supplied by solar, and auxiliary usage was heavy. Moderate to light heating loads during the rest of the month were met entirely by solar, but conditions during the eight cold, cloudy days heavily affected the monthly average.

It is instructive to observe from these results that (a) assertions that cold weather is almost invariably sunny are incorrect and (b) a storage volume even three times the size used would not have avoided the need for auxiliary use during the last day or two of November.

B. Collector Comparison

Comparison of the data on the system employing evacuated tube collectors with the flat-plate results shows, in Fig. 6 and Table 2, (a) high solar collection, high collector efficiency, and high fraction of space heating load carried by solar, (b) higher solar hot water delivery, but less than can be obtained by relocating the hot water exchanger, and (c) over half of the large cooling requirements met by solar.

Radiation data are based on total area occupied by the evacuated tubular array, about half of which is effective absorber area. Based on this total area, the fraction collected is about double the flat-plate figure. Per unit absorber area, the improvement is nearly fourfold.

C. Cooling Comparison

Although very limited cooling data were obtained with the flat-plate system in October, it is evident that major improvements resulted from the change to evacuated tube operation. The portion of the cooling load carried by solar was about 53% (compared with 43% and 63% in August and September 1977), but the August and September cooling loads were over five times as great as in the previous October. Total energy required for cooling (solar plus auxiliary) in August and September was almost as high as the heating needed in January, February and March. The solar supplied to cooling, 344 and 402 MJ/day in August and September, at an average COP of 0.6, provided about 18 ton-hours of cooling per day (63 kWh/day) which would normally be fully sufficient for a comparable residence in the Fort Collins summer climate. The much higher cooling demand in CSU Solar House I is due to heat losses from the storage tank and other hardware in the equipment room, high electricity use for instruments, motors, and lighting at office intensities, and to heat generation by two to three times the normal residential human occupancy. Cooling data in a previous report [2] on CSU Solar House I are based on use of an earlier model air conditioner of the direct expansion type, so comparisons cannot show the sole effect of collector type. However, monthly and seasonal solar use for cooling in 1975 and 1976 were considerably less than in the summer of 1977, further supporting the combined advantages of using more efficient collectors and a cooling machine having a wider supply temperature.

III. System Economic Analysis

A. Fuel Savings

The fuel savings obtainable with the solar energy systems in CSU Solar House I are shown in Table 4. The figures are derived from the results in Table 2 and from the furnace efficiencies and COP values shown. Because equipment efficiencies vary over a wide

	DHW [1]	Space Heating	Space Cooling [2,3]		Totals	
Oct '76	2,260	113	-1,783	3,442	590	5,815
Nov '76	2,122	6,941	163	163	9,226	9,226
Dec '76						
Jan '77	1,703	17,057	0	0	18,765	18,765
Feb '77	1,774	17,491	0	0	19,265	19,265
Mar '77	2,713	24,509	0	0	27,222	27,222
Apr '77	5,515	8,886		0	14,401	14,401
May '77						
Jun '77		No data available				
Jul '77						
Aug '77	3,477	0	11,577	16,681	4,634	20,158
Sep '77	2,310	0	13,897	18,852	16,207	21,162
Annual Totals	21,879	74,997	23,854	39,138	120,730	136,014

[1] Gas hot water heater has a measured combustion efficiency of 82% under ideal standard test conditions*

[2] Gas boiler has a measured combustion efficiency of 77.7% under ideal standard test conditions*

[3] COP of Arkla chiller for Oct and Nov was .48, for Aug and Sep the COP was .64

*Various references show that average combustion efficiencies of residential gas furnaces and water heaters, operated for extended periods of time with minimum servicing and adjustment, rarely exceed 50% Figs. shown in the table should therefore be considered the minimum or "ideal" savings in fuel, normally at least half again as large.

Table 4. Minimum Monthly and Annual Energy Savings, MJ

range, depending on many operational factors, these savings must be considered theoretical minima based on measured heat <u>delivery</u> performance. Fuel savings involve <u>supply</u> considerations, in which uncertain <u>average</u> combustion efficiencies should be used.

Two types of savings are shown for solar cooling. Column 3 shows actual savings resulting from the use of the solar cooling system, penalized by solar heat losses into the building mainly from solar storage. This solar heat leakage adds to the cooling required, so the fuel savings are less than if such heat leakage could have been discharged outside the builling without adding to the cooling load. In fact, in October, the negative saving means that the solar system lost more heat into the building than the cooling it could supply.

Column 4 shows the fuel savings that could have been achieved if the heat losses from the hot solar system components inside the building could have been discharged outdoors without adding to the cooling requirements.

Table 4 shows that the solar system with evacuated tubular collectors saved about 110,000 MJ (roughly 100 million Btu) in six months of operation, that it could probably reach 130000 MJ savings if better system insulation were used (reducing cooling load as well as increasing solar energy available for cooling operation), and that water heater relocation might add another 10,000 MJ savings.

if a probable average gas combustion efficiency of 50% were being realized, these total savings would reach about 200,000 MJ of fuel heating value. The six months of operation are reasonably representative of the year, so it appears that savings of 300,000 to 400,000 MJ per year are possible with this system.

IV. Conclusions

It is concluded that the system comprising an evacuated tubular collector, lithium bromide absorption water chiller, and associated equipment is highly effective in providing solar heating and cooling to a small building, that it can supply up to twice the space heating and several times the cooling obtainable from an equal area of good quality flat-plate collectors, and that a greater fraction of the domestic hot water can be obtained by supplying its heat from main storage. The cost-effectiveness of the system, in comparison with one employing a good flat-plate collector, can be determined when commercial pricing data are made available.

Acknowledgement

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