DESIGN, CONSTRUCTION, AND TESTING OF A
RESIDENTIAL SOLAR HEATING AND COOLING SYSTEM

Annual Progress Report
for the period

1 July 1974 to 1 February 1975

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Residential Solar Heating and Cooling System

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Annual Progress Report Covering the Period

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Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation or the Energy Research and Development Administration.

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Statement of Objectives

This project is a nominal two-year effort to design, construct, test, and evaluate an experimental system for utilizing solar energy to drive heating, cooling, and hot water subsystems, supplemented as necessary with auxiliary (oil or gas) fuel.

The program is designed to provide the following information:

- a. design data for integrated systems and the various subsystems,
- b. system performance for heating, cooling, and water heating,
- c. operating economics,
- d. verification of the University of Wisconsin model,
- e. design and operation of automatic controls,
- f. correlation of standard Weather Bureau data with on-side insolation data, and,
- g. system reliability evaluation.

System design has been accomplished during the first five months and construction completed during the following five month period. Operation and evaluation through a summer air conditioning cycle and a winter heating cycle are being made during the period 1 September 1974 to 30 August 1975.

The refrigeration system consists of a specially modified LiBr/water absorption system operated with hot water. The building is designed so that the various subsystems can be removed and replaced, so that the facility can serve in the evaluation of other solar components and systems. This project will derive information which should be useful in the Heating and Cooling of Buildings Proof-of-Concept Experiments Program and will provide a facility for evaluating subsystems developed for that program.

TABLE OF CONTENTS

	Page
Cover Sheet.	i
Author Sheet	ii
Disclaimer Notice.	iii
Statement of Objectives.	iv
Table of Contents.	v
List of Figures.	vi
List of Tables	vii
Abstract	viii
Narrative.	1
Introduction.	1
Progress on Objectives.	2
Problems Encountered.	3
Plans for Next Reporting Period	4
Assessment of Next Reporting Period	4
Summary of Research Results.	6
Cooling System Performance.	6
Heating System Performance.	18
Collector Performance	20
Research Utilization	29
Appendices	40
A. List of Research Contributors	41
B. Bibliography of All other Reports and Papers Generated	42
C. Research Distribution List.	44
D. Research Utilization Handouts - General Public.	48

LIST OF FIGURES

Figure	Title	Page
1.	Preliminary Performance of Solar Heating and Cooling System - Incident Solar Radiation, Useful Heat Recovered, Solar and Gas Energy Supplied to Load for Period 1 August 1974 to 31 January 1975	7
2.	Relative Contributions to Cooling Unit by Solar and Auxiliary (August 1974)	9
3.	Relative Contributions to Cooling Load by Solar and Auxiliary (August 1974)	14
4.	Coefficient of Performance and Cooling Rate versus Time of Start Up for Absorption Cooling Unit.	15
5.	Relative Contributions to Cooling Load by Solar and Auxiliary (Normal Cooling Load Only).	17
6.	Relative Contribution to Heating Load by Solar and Auxiliary (18 December 1974 - 31 January 1975).	19
7.	Relative Contribution to Hot Water Load by Solar and Auxiliary (August 1974)	21
8.	Relative Contribution to Hot Water Load by Solar and Auxiliary (January 1975).	22
9.	Collector Efficiency versus $\Delta T/HR$ (Test Module)	23
10.	Thermal Storage Temperature versus Time of Collector Start Up.	27

LIST OF TABLES

Table	Title	Page
1.	Preliminary Performance of Solar Heating and Cooling System - Weekly Totals of Energy Loads.	8
2.	Relative Contributions to Cooling Load by Solar and Auxiliary (August 1974) - Ten-Day Totals.	11
3.	Average Daily Collector Efficiencies for Period 1 August 1974 - 31 January 1975	25
4.	Recorded Visitation Figures for Period 1 January 1975 - 15 May 1975.	30
5.	Education Groups Visitation (January 1, 1975 to May 15, 1975)	31
6.	Spectrum of Visitors by Geographic Location	32
7.	Spectrum of Visitors by Organization (VIP).	33
8.	Lectures, Talks, and Papers Presented by Principal Project Members (January 1, 1975 - May 15, 1975).	35

Abstract

The NSF/CSU Solar House I solar heating and cooling system became operational on 1 July 1974. During the first months of operation the emphasis was placed on adjustment, "tuning", and fault correction in the solar collection and the solar/fuel/cooling subsystems. Following this initial check out period, analysis and testing of the system utilizing a full year of data was begun. This progress report discusses the preliminary performance of the heating and cooling system.

During the period 1 August 1974 through 31 January 1975, approximately 40% of the cooling load was provided by solar energy. Solar heating over the same period of time provided 86% of the space heating load and 68% of the domestic hot water heating load. These percentages represent a total solar contribution of 33,996 MJ delivered to load (8,061 MJ to the cooling unit; 20,687 MJ to heating; 5,248 MJ to hot water). Natural gas accounted for 22,442 MJ, total.

Preliminary analysis has provided several significant results associated with the operating characteristics of the solar system and the individual components. The requirement for a 10-15 minute warm-up period yielded, under conditions of low cooling demand, a substantial decrease in the ARKLA 3-ton, Lithium Bromide absorption unit Coefficient of Performance (C.O.P.). Variations in control systems methodologies were also affected by the cooling unit warm-up requirements, and significant differences under different operating conditions were evident.

Heat losses from the thermal storage tank, preheat, and hot water tanks, pumps, piping, heat exchangers, and other components of the system indicated the critical necessity of effective insulation. The additional cooling load imposed by thermal losses accounted for almost half of the total cooling demand during the month of August. Heat losses during the heating season did not substantially affect auxiliary fuel requirements, since the heat is utilized in heating the building. Heat losses from the auxiliary boiler and gas hot water heater, however, were principally due to air continually rising through the boiler tubes to the stack and outdoor atmosphere, thereby being lost to the building.

Collector efficiency ranged from 30-35% throughout the period 1 August 1974 to 31 January 1975, where efficiency is defined as the useful solar energy delivered to thermal storage (or load) divided by the solar radiation incident on the collector during the operation of the collector. If we define daily collector efficiency as the useful energy delivered divided by the total daily solar radiation, the daily collector efficiency varies from 20-25% for the period August through January. These average collector efficiencies are at satisfactory and expected levels, consistent with the high average temperatures of collection - in summer because of usage above 80°C, and in winter because of moderate heat demand and high average storage temperature.

NARRATIVE

Introduction

On 19 September 1973, the Solar Energy Applications Laboratory of Colorado State University received a grant from the National Science Foundation (Research Applied to National Needs) for the Design, Construction, and Testing of a Residential Solar Heating and Cooling System. The planning and design efforts accomplished during the first four and one-half month period (September 1973 through January 1974), are described in the annual progress report, "Solar Heated and Cooled Building" (NSF/RANN/SE/GI-40457/PR/74/4). A second progress report, "Design and Construction of a Residential Solar Heating and Cooling System (NSF/RANN/SE/GI-40457/PR/74/2) was submitted in August 1974, and described the details of the solar heating and cooling systems design, its fabrication and installation, and the principles involved in the operation of the building, HVAC system, and data instrumentation. This third progress report provides preliminary information on the operating performance of the solar heated and cooled house (hereafter referred to as CSU Solar House I).

The primary emphasis of this report is on the operation of the heating and cooling system during the period from 1 August 1974 to 31 January 1975. During this period some operational difficulties (described below) prevented a continuous monitoring of system performance. The most troublesome problem was intermittent failure of the data logging unit to record sensor outputs for subsequent computation and analysis. Accordingly, some of the data were obtained by manual readings, the analysis of which was performed without the aid of a computer. The primary difficulty arising from this

failure in the instrumentation was the unavailability of data during the period from 5 P.M. to 8 A.M. during the month of August. This problem was effectively resolved by 1 September. In addition, a malfunction of the digital instrumentation during the month of December caused the loss of approximately one week of data.

Progress on Objectives

The primary objectives of the project are:

- (1) To establish the practicality of space cooling with solar energy,
- (2) To design an effective and economical system for residential heating and cooling and service hot water heating with solar energy,
- (3) To construct a fully automated and instrumented solar heating and cooling system in a new residential building,
- (4) To appraise the performance of the complete heating and cooling system and each of its principal components,
- (5) To determine which of several operating modes minimizes auxiliary energy requirements,
- (6) To appraise the utility of a mathematical model in design and prediction of performance by comparing actual and predicted results, and,
- (7) To modify system design and operation in an effort to minimize the total annual cost of heating and cooling.

The accomplishment of objective (1) is, of course, an ongoing process. However, the early results obtained during the first operational period indicate no substantial difficulties in establishing the practicality of space cooling with solar energy. Heat has been provided by the solar system

at a temperature sufficient for operation of the lithium bromide absorption unit without any maintenance or operational difficulties.

Objectives (2) and (3) have been met in large part. Only the question of economic effectiveness remains open. Studies associated with objectives (4), (5), and (6) are now in progress, and this report discusses the early results directed to objective (4). Modifications in the system (objective (7)) will be made as indicated by the results of the operational data and analysis (see Plans for Next Reporting Period).

Problems Encountered

No major problems have been encountered in the operation of the building and the solar heating and cooling system. The lithium bromide absorption cooling unit has operated with no difficulties, but its efficiency can be improved by some adjustments to be made during the summer of 1975. There has been no damage or deterioration or maintenance required in the collector-storage assembly, and the heating and cooling system has performed essentially as expected.

The only problems encountered have been associated with the automatic data recording system. Intermittent failure of the recording equipment precluded acquisition of continuous records. The "manual" data which therefore had to be collected could not be continuously recorded, nor was it practical for data to be secured at night when the building was not occupied. The data thus collected were in an inappropriate form for computer analysis, so much of the early information required analysis by hand.

An associated problem has been in obtaining reliable integrated values for specific data inputs. In some cases data were available only as

instantaneous values, the averaging of which is less accurate than integrated totals. (The integrated solar radiation data, however, was provided by a separate data system, which provided a printed record of integrated solar radiation data.) The problem resulted from inaccurate automatic resetting of the integrators for specific function (e.g., gas usage to hot water and auxiliary boiler) after a regular scan by the data acquisition system, thereby producing "parity errors" on the magnetic tape. Parity errors make a magnetic record of data useless unless eliminated by rewriting of the data tapes. Where necessary, these errors have been corrected.

Plans for Next Reporting Period

An analysis of the heating and cooling system during a complete year is now in progress, and will be completed during the next reporting period. Comparisons of different operating modes will be made for both the heating and cooling seasons.

To maximize cooling system effectiveness, increased thermal insulation will be applied to the individual heating and cooling system components as well as in the general equipment area. An arrangement for venting heat losses from the heating and cooling system to the building's exterior will be designed and implemented.

Assessment of the Next Reporting Period

No difficulties are expected to be encountered in carrying out the plans for the next reporting period. The data acquisition and instrumentation system is now functioning properly and no additional difficulties are expected in this area.

The approximate percentage of time or effort which the principal investigator has devoted to the project since the beginning of the current term of the agreement is 25% of time for nine months (1 October to 30 June). The principal investigator expects to devote to the project 33% of time during the remainder of the current term (1 July to 30 September).

SUMMARY OF RESEARCH RESULTS

The NSF/CSU Solar House I solar heating and cooling system became operational on 1 July 1974. During the first months of operation the principal purposes were the adjustment, "tuning", and fault correction in the solar collection and the solar/fuel/cooling subsystems. Precise determinations of seasonal cooling performance in terms of collector efficiency, Coefficient of Performance (C.O.P.), portion of total cooling load carried by solar and by fuel, were planned for the summer of 1975, in order that the best conditions of operation could be ascertained and maintained through an entire cooling season.

Preliminary performance of the heating and cooling system is shown in Figure 1 and Table 1. Weekly totals of incident solar radiation (H_R), useful heat delivered to thermal storage (Q_U), and total loads met by solar and auxiliary fuel are shown for the period 1 August 1974 through 31 January 1975. Approximately 40% of the normal cooling load was provided by solar energy. Solar heating has provided 86% of the space heating load and 68% of the domestic hot water heating load. These percentages represent a total solar contribution of 33,994 MJ (8,061 MJ to cooling unit; 20,687 MJ to heating; 5,248 MJ to hot water). Natural gas accounted for 22,442 MJ, total.

Cooling System Performance

Figure 2 shows the relative contributions of the solar-generated and auxiliary heat delivered to the cooling unit during the month of August.

Figure 1. Preliminary Performance of Solar Heating and Cooling System - Incident Solar Radiation, Useful Heat Recovered, Solar and Gas Energy Supplied to Load for Period 1 August 1974 to 31 January 1975.

Table 1
WEEKLY TOTALS OF ENERGY LOADS

Week (1 Aug- 31 Jan)	Solar ¹ H _R (45°) (MJ)	Q _U (MJ)	Total Load Met by Solar (MJ)	Total Load Met by Gas (MJ)	Solar Cooling (MJ)	Solar Heating (MJ)	Solar Storage Losses (MJ)	Solar to Hot Water (MJ)	Gas Cooling (MJ)	Gas Heating (MJ)	Gas to Hot Water (MJ)
1	10,321	1,493	1,178	1,787	612	101	370	95	1,625	--	162
2	9,677	1,445	1,318	1,558	676	151	363	128	1,403	--	155
3	10,147	1,355	1,271	2,079	554	80	380	257	1,952	--	127
4	11,080	2,218	1,772	1,600	1,219	45	390	118	1,459	--	141
5	8,280	924	1,243	1,525	641	40	363	199	1,434	--	91
6	7,995	1,225	1,443	1,923	784	86	321	252	1,857	--	66
7	6,013	1,532	1,262	929	536	161	291	274	856	--	73
8	8,237	1,626	1,476	1,421	940	14	363	159	1,360	--	61
9	11,335	2,390	1,955	1,228	1,256	40	383	276	1,033	--	195
10	6,103	1,169	1,487	2,700	709	93	356	329	(2)2,633	--	67
11	7,086	1,454	738	448	42	76	318	302	396	--	52
12	522	149	967	311	92	81	315	479	284	--	27
13	5,885	1,147	957	92	--	313	331	313	--	--	92
14	5,557	1,145	1,045	81	--	531	290	224	--	--	81
15	5,954	1,244	1,269	105	--	748	313	208	--	--	105
16	1,556	--	829	98	--	411	317	101	--	--	98
17	7,258	1,032	1,731	110	--	1,218	292	221	--	--	110
18	9,031	1,042	1,528	85	--	979	270	279	--	--	85
19	7,249	1,343	1,667	81	--	1,259	229	180	--	--	81
20	No Data										
21	6,530	1,492	856	1,160	--	605	146	105	--	1,076	84
22	7,249	1,976	2,083	352	--	1,731	191	161	--	239	113
23	7,116	1,777	1,925	274	--	1,546	198	181	--	158	116
24	5,545	1,254	1,201	1,484	--	935	144	122	--	1,277	207
25	7,840	1,898	1,515	164	--	1,150	235	130	--	3	161
26	5,178	1,014	1,278	847	--	982	143	153	--	621	226
Totals	178,744	33,344	33,994	22,442	8,061	13,376	7,311	5,248	14,185	3,374	2,776

¹ Total incident radiation on 768 ft² collector (45° tilt)

² Large gas use due to severe cycling of cooling unit (e.g., 5 October data) [C.O.P. 0.2]

Preliminary Performance of Solar Heating and Cooling
System - Weekly Totals of Energy Loads

Table 1

FIGURE. 2. Relative Contributions to Cooling Unit by Solar and Auxiliary (August 1974)

The cooling load of the building, however, is not representative of typical home cooling loads due to an excessive number of people occupying and visiting the building. Because of the approximate 3,000 persons visiting the NSF/CSU Solar House I during the month of August, the total percentage load carried by solar is of less significance than the total solar energy provided for cooling purposes. More important is the cooling load carried by solar heat under various control procedures.

During the period 1-10 August, a secondary control was utilized in selecting solar or auxiliary to meet the cooling load. A double thermostat provided for cooling by solar whenever the temperature in the building rose above 22°C (71.6°F) and the temperature of thermal storage exceeded 82°C (180°F). If the cooling demand could not be met and the house temperature continued to rise above 23.4°C (74.1°F), auxiliary would then be used to supply heat to meet the full cooling load even though the storage temperature exceeded the minimum required inlet temperature to the generator of the cooling unit.

This control system was modified on 10 August, to provide solar cooling whenever the thermal storage temperature exceeded the minimum generator inlet temperature (82°C , 180°F). The period of operation from 11-20 August shows the benefits (Figure 2) of the control instrumentation modification, by increasing the solar energy delivered to the cooling unit from 612.4 MJ to 1048.8 MJ. An equally dramatic improvement was obtained for the last ten days of August by lowering the minimum required temperature to the cooling unit generator from 82°C (180°F) to 77°C (170.6°F). The increase in total solar energy delivered to the cooling unit as a result of the lower generator temperature requirement was 500 MJ (~ 50 MJ/day). Table 2 summarizes these effects of the control system modifications.

Table 2

Relative Contributions to the Cooling Load by
Solar and Auxiliary (August 1974) - Ten Day Totals

Time Span	* Cooling Gas (MJ)	Solar (MJ)	Percent Solar Cooling	Q_U (MJ)
1-10 August	1011.8	364.7	26.5	2,143.5
11-20 August	1442.8	745.8	34.1	2,824.1
21-30 August	946.2	1192.2	55.8	3,882.6
TOTAL	3400.8	2302.7	40.4	8,850.2

* MJ of heat removed from building by cooling unit.
(Heat delivered to cooling load times Coefficient of Performance)

Because of the low humidity conditions existing in CSU Solar House I, most of the operating data were obtained during periods when no condensation occurred in the cooling unit. Absence of dehumidification substantially reduced the Coefficient of Performance of the unit. This is to be expected since, for an input of 56.5 MJ/hr (53,500 Btu/hr), the unit can deliver sensible cooling of only 28.5 MJ/hr (26,980 Btu/hr), the balance of 10.6 MJ/hr (10,050 Btu/hr) being latent heat removal by condensation. When the latent load is zero, the C.O.P. is thus reduced from 0.69 to 0.50. Typically, the average C.O.P. of the cooling unit when on auxiliary heat supply was 0.48 (11-30 August).

Of particular note, however, is the fact that the solar heat to the cooling unit during the same period yielded an average C.O.P. of 0.70. This higher value was due to a combination of a lower hot water flow rate to the generator when the solar storage was supplying heat to the cooling load, and a lower average operating temperature of the storage unit compared with auxiliary heat supply temperatures. The heat input rate to the generator thus decreased from 56.5 MJ/hr (as in the case of gas-supplied heat) to 40 MJ/hr (average for solar), a heat rate which could be expected to deliver 32.3 MJ/hr of combined sensible and latent cooling (85% of capacity). This heat removal rate nevertheless exceeds the 28.5 MJ/hr sensible cooling load. The reduced heat supply rate nearly matched the sensible heat removal requirements (condensation being absent), less heat was therefore wasted than when the design heat supply rate was provided, and a favorable solar C.O.P. of 0.71 (28.5 MJ/hr divided by 40 MJ/hr) was obtained. This value is in good agreement with the daily average C.O.P. of 0.70.

Because of the improved C.O.P. of the solar supplied cooling, the percentage load of cooling (actual heat removed from the building) provided

by solar is increased from 36% to better than 40%. Figure 3 shows the cooling load met by solar and auxiliary during the month of August. Note also Table 2, which shows that under the optimum conditions of the last ten days of August, solar accounted for almost 56% of the cooling load.

The change in the control instrumentation, mentioned above, also had the effect of increasing the C.O.P. when operated by auxiliary from an average of 0.43 to 0.48. When solar operated, the modification caused an increase in C.O.P. from 0.60 to 0.70.

A much more significant variation in the C.O.P. of the cooling unit is due to its operating characteristics, particularly during start-up. Figure 4 is an example of the manner in which cooling performance varies during a period of time. Point A represents the time at which the thermostat initially provides a cooling demand signal (when the absorption unit comes on). The gradual rise of the heat supply curve (Q_L) shows that the initial heat delivered to the cooling unit is used partially to warm up the unit (prior to operation at normal cooling capacity) for a period as long as fifteen minutes. The delivery of full cooling output is also delayed, as shown by the $Q_{CT}-Q_L$ and C.O.P. curves.

During days of high cooling demand, the cooling unit undergoes these start-up conditions and then runs nearly continuously at a satisfactory C.O.P.. The loss of cooling during start-up becomes negligible and the C.O.P. for the day corresponds to the design value. However, when cooling demand is low, the unit runs intermittently, and the numerous start-ups (as many as 40 in a 24 hour period) require heat to replace the thermal losses occurring during the non-running intervals. The unit cools off in about ten minutes, so if it runs only ten minutes, the heat losses in one

FIGURE 3. Relative Contributions to Cooling Load by Solar and Auxiliary (August 1974)

SOLAR HOUSE RAW DATA PLOTS

10 5 74

QL

QCT-QL

COP

FIGURE 4. Coefficient of Performance and Cooling Rate versus Time of Start Up for Absorption Cooling Unit

stop-start cycle result in a C.O.P. decrease from 0.60 to about 0.30. It is significant that the start-up heat is added to the building when the cooling unit shuts down, so the cycling of the absorption machine not only causes a lowering of the C.O.P., but also adds to the cooling load.

Inefficiencies resulting from intermittent operation of the air-conditioner could be greatly reduced by use of cold-side storage. The absorption unit could be run continuously during the day so that waste of heat involved in frequent cycling could be avoided.

Other additional cooling loads not normally encountered in conventional systems were imposed by the thermal losses from solar components. Measurements of losses from the solar thermal storage tank, for example, showed a rate of $0.04 \text{ MJ/hr} \cdot ^\circ\text{C}$ (approximately double that computed from reported properties of the insulation). During the month of August there was an average heat loss rate of 1.88 MJ/hr (1780 Btu/hr). This 45 MJ/day heat loss (1395 MJ/month) can be compared to the hourly sensible heat removed by the cooling unit (ranging from 22.8 to 28.4 MJ); i.e., the cooling unit must operate for almost two hours per day to remove the heat added to the house by leakage from storage.

Adding a heat loss from the solar preheat tank (hot water system) of 0.492 MJ/hr (372 MJ/month), and other losses from the surface of the auxiliary hot water tank, pumps, piping, and heat exchangers, the 2619 MJ additional cooling load due to thermal losses from the system during August accounts for 46% of the total cooling demand of 5703 MJ . Had these losses been eliminated, solar heat would have provided 74.7% of the cooling requirements. Figure 5 indicates the relative contributions of solar and gas heat delivered to the cooling unit when these thermal losses are eliminated. Losses during the heating season do not appreciably

FIGURE 5. Relative Contributions to Cooling Load by Solar and Auxiliary (Normal Cooling Load Only)

affect auxiliary fuel requirement because the heat is utilized in heating the building directly.

Substantial progress in the reduction of these heat losses has been made in preparation for the next cooling season. These efforts are directed toward better insulation of equipment and the venting of excess heat from the heating and cooling system components, directly to the building's exterior.

Heating System Performance

Heat losses from the solar components during the heating season contribute to the supply of heat for the building. Thus the solar contribution to the heating load is equal to the useful energy delivered from the solar collectors to the thermal storage unit. Figure 6 is a plot of solar and auxiliary heat supplied for space heating during the period 19 December 1974 to 31 January 1975. Prior to 18 December 1974, solar provided 100% of the heating load.

Gas usage is seen to be primarily during periods of high heat demand, and only on six days did it have to supply more than half the total requirements. There were no days during which fuel supplied the full load.

An important influence on the auxiliary energy required by the heating and cooling system is exerted by the operating characteristics of the auxiliary gas boiler. Present control instrumentation requires the maintenance of a pre-set temperature in the boiler. Gas required simply for this temperature maintenance can be a significant portion of the total usage because of limited fuel heat demand (auxiliary heat was required only 20 days out of 123 during the period 1 October 1974 to 31 January 1975). The principal heat loss from the boiler is to air continually rising through the hot boiler tubes to the stack and outdoor atmosphere.

The boiler in CSU Solar House I was found to require 120 cubic feet of gas/day when thermostatted at 190°F (cooling season) and 80 cubic feet of gas/day at a setting of 150°F (heating season). During the month

DAY OF THE MONTH (19 Dec. '74 - 30 Jan. '75)
 FIGURE 6. Relative Contribution to Heating Load by Solar and Auxiliary

of August the requirements of a "hot boiler" accounted for more than 5% of the total gas volume utilized. In the heating season, the hot boiler condition required 6330 MJ out of a total gas usage of 9480 MJ; i.e., two-thirds of the gas usage was for maintaining boiler temperature. Consideration of a "cold boiler" system, characterized by substantially lower thermal losses, is therefore being made.

Solar energy provided 68% of the service hot water requirements during the period 1 August 1974 through 31 January 1975. Figures 7 and 8 show the solar and gas heat supplied to the domestic hot water in August and in January. Hot water usage in August was only 3,030 ℓ (800 gallons) or about 100 ℓ (27 gallons) per day. This low rate of flow through the gas heated tank and the long residence time therein result in high thermal loss rates and fuel use per unit volume delivered. Programmed hot water consumption in the winter months provided a more realistic pattern of auxiliary fuel requirements.

Collector Performance

Collector efficiency as a function of temperature and incident solar radiation was experimentally determined by operation of a collector test module, the results of which are shown in Figure 9. Efficiency is plotted against $\Delta T/H_p$, where ΔT is the difference between the temperature of the inlet water to the collector and the atmosphere, and H_p is the incident solar radiation on a 45° tilted surface. The efficiency is defined as the useful energy delivered divided by the incident solar radiation.

Typical operating conditions involve a temperature difference of 50 to 55°C and an incident radiation of 1.1 to 1.3 ly/min. These conditions

FIGURE 7. Relative Contribution to Hot Water Load by Solar and Auxiliary (August 1974)

FIGURE 8. Relative Contribution to Hot Water Load by Solar and Auxiliary (January 1975)

FIGURE 9. Collector Efficiency Versus $\Delta T/HR$ (Test Module)

provide an effective operating range of $\Delta T/H_R = 50^\circ\text{C min/ly}$ to $\Delta T/H_R = 38^\circ\text{C min/ly}$; corresponding to a collector efficiency of 27 to 35%. However, this instantaneous collector efficiency is obtained under steady state conditions and is not representative of typical operation in a house heating system. A more useful measure is the mean daily collector efficiency as defined in one of two ways. η_D is the total daily useful energy delivered to load (or thermal storage) divided by the total measured incident solar radiation during the full day, H_R ; η_{DO} is the total useful energy delivered to load (or thermal storage) divided by the incident solar radiation received during the operating hours of the collector.

Table 3 lists the mean monthly values of daily efficiency and the daily efficiency (during collector operations) for the period 1 August 1974 through 31 January 1975, as well as total daily solar radiation and radiation during collector operation. Although daily efficiency based on solar energy during operating hours was fairly constant, month-to-month, efficiency based on daily total radiation varies considerably. Most of the differences in the latter set of figures are due to variation in periods of collector operation, caused in turn by seasonal changes in storage temperature, atmospheric temperature, and hours of sunshine.

Efficiencies of 30 to 35% when operating, and 20 to 25% based on total daily solar radiation may appear lower than expected of a well-designed, double-glazed collector. But these levels are very satisfactory at the high average temperatures of operation which usually prevailed. During the summer, storage temperatures equalled or exceeded 80°C most of the time, so $(T_{in} - T_{ambient})$ usually exceeded 60°C (108°F). The high percentage of seasonal heating load carried by solar (86%) and the fact that 100% of the load was met by solar until 18 December,

Table 3

Month	Average η_{DO} (%)	¹ Average H_{RO} (1y/day)	Average Ambient T_{AO} (°C)	Average Storage T_{SO} (°C)	² Average η_D (%)	² Average H_R (1y/day)
August	33.3	332	25.1	76.8	20.2	492
September	31.5	265	16.4	72.0	22.5	370
October	30.5	197	13.4	73.9	21.2	284
November	31.2	164	3.7	63.6	19.6	261
December	33.3	230	2.4	50.0	23.8	320
January	33.0	249	2.9	46.3	24.6	334

¹ Includes solar radiation only when collector is operating

² Includes days when collector did not operate at all

mean that fall and winter average storage temperatures were high (generally above 50°C), so collector efficiency was limited by the elevated temperature. The self-regulating effect of temperature on efficiency is clearly evident - ample heat in storage causes a reduction in collection efficiency because of high inlet temperature. This efficiency decrease is not a penalty, however, because it occurs when high collection is not needed and, in fact, not usable.

Alternating cloudy and sunny periods can adversely affect collector efficiency by increasing start-up losses. During start-up of the solar collector, liquid is supplied to it from the thermal storage exchanger, and solar radiation provides the energy to heat the fluid to operating temperatures. The collector pump cycles on and off while the collector loop fluid is heated to a temperature consistent with a continuously operating condition. However, as the sun heats the fluid in the collector panels to a temperature exceeding storage temperature by a preset amount (typically $3\text{--}10^{\circ}\text{C}$), the collector pump is started, and the heated fluid in the collector is replaced by the cold fluid in the piping. The temperature difference between collector panel and storage drops, and the collector pump shuts off. In this same interval, the cold fluid in the piping on the outlet side of the collector is being pumped through the heat exchanger and heated by the thermal storage unit.

Figure 10 is a plot of the thermal storage tank temperature during the first hour of collector operation on three days. The upper curve (I) represents the conditions when the thermostat was set at a temperature difference between collector and storage of 10°C . Of the required 17.8 MJ to heat the collector fluid from ambient to operating temperature, 10.1 MJ were drawn from storage. When the collector operation ceases, usually only at the end of the day, most of the heat in the collector and the

FIGURE 10. Thermal Storage Temperature versus Time of Collector Start Up

collector fluid (largely in the piping in the unheated attic space) is lost to the surroundings. Since the collector efficiency is based on useful heat delivered to storage (or load), any cycling of the collector subsystem due to alternating cloudiness/sunshine would significantly increase the effective heat losses from the solar collector.

Cases II and III are for a thermostat setting of 3°C. This lower thermostat setting causes an increase in the heat drawn from storage to 14.7 MJ of the 17.8 MJ required (83% of the heat required for the collector comes from storage). This increase in use of storage heat for the collector loop heating due to a lower thermostat setting is due to less collector pump cycling (on and off) at the higher setting. This is reasonable since, for a higher thermostat setting, more heating of the solar collector is required, thus implying a higher rate of solar insolation (and, commonly, later in the morning). In Case III, a cloudy condition increases to 96% the portion of the collector preheat requirements met by withdrawal from storage. This increase is due to the longer period required to bring the collector loop up to operating temperature, thereby making heat losses from the collector more significant. The effect of poor solar conditions is to cause sufficient collector pump cycling to extract heat from storage without obtaining useful energy from the solar collector.

RESEARCH UTILIZATION

Utilization and dissemination of the research results from CSU Solar House I has been extensive. The project has received considerable public visibility as a result of the research activities, from press releases (both locally and nationally), and as a result of hosting the ISES conference. As a conservative estimate, over 8,000 visitors have toured Solar House I in the first nine months. Detailed lists of visitors are shown in Tables 4 through 7, in several classifications. Visitors from every state except Alaska, and 26 foreign countries have toured the facility. The interests of visitors have ranged from quick look-see to detailed inquiries into the design, construction, operation, and performance of the solar heating and cooling system. While the occupants of Solar House I have taken the bulk of these visitors, the staff not housed in Solar House I have also provided guided tours for individuals and groups on Saturdays, Sundays, and holidays.

Based on the calculated figure of 27 individuals visiting the CSU Solar House I laboratory each working day, the total estimated visitation for the period 15 July 1974 through 15 May 1975 (226 working days) is 6102 individuals. In addition, the International Solar Energy Society conference held in August of 1974 had 960 members registered, which including their families, accounted for 2390 individuals seeing the Solar House I facility. Of this number, two-thirds (5660 individuals) may be considered "drop-ins" in that they were not members of a scheduled tour or group visit.

Table 4

Recorded Visitation Figures for
January 1, 1975 through May 15, 1975

Month	Scheduled	Drop-Ins	Total
January	215	115	330
February	365	191	556
March	380	210	590
April	443	153	596
May 1-15	172	131	303
Totals	1575	800	2375

Table 5
Educational Group Visitation

Educational Level	Number of Tours	Number of * Individuals
Grade School Grades 1-6	3	60
Junior High and High School Grades 7-12	14	280
University (Post High School)	9	180
Continuing Education	4	80
Total	30	600

* The average size of each group was 20 individuals

Table 6

Spectrum of Visitors by Geographic Location

United States			
Alabama	4	Nebraska	23
Arizona	16	Nevada	5
Arkansas	2	New Hampshire	4
California	93	New Jersey	10
Colorado	997	New Mexico	27
Connecticut	13	New York	31
Delaware	5	North Dakota	4
Florida	14	North Carolina	5
Georgia	4	Ohio	25
Hawaii	6	Oklahoma	16
Idaho	5	Oregon	7
Illinois	38	Pennsylvania	24
Indiana	16	South Carolina	3
Iowa	28	South Dakota	7
Kansas	32	Tennessee	14
Kentucky	5	Texas	39
Louisiana	7	Utah	5
Maine	4	Vermont	5
Maryland	19	Virginia	19
Massachusetts	8	Washington	6
Michigan	11	Washington, D.C.	19
Minnesota	16	West Virginia	2
Missouri	19	Wisconsin	11
Montana	8	Wyoming	29
Foreign Nations			
Argentina	1	Italy	4
Australia	5	Japan	23
Austria	2	Mexico	33
Brazil	3	Norway	1
Canada	17	Netherlands	2
Columbia	5	Puerto Rico	1
Denmark	3	Saudi Arabia	1
England	3	South Africa	2
Finland	2	Spain	3
France	5	Suriname	2
Germany	2	Sweden	4
Guam	2	Switzerland	5
Iran	7	U.S.S.R.	7

Table 7

Spectrum of Visitors by Organization

<u>State of Colorado</u>	<u>Federal Agencies</u>
<ul style="list-style-type: none"> 2 Governors 2 State Senators 3 State Representatives 1 Secretary of State 1 Colorado Energy Research Institute Director 	<ul style="list-style-type: none"> 7 National Science Foundation/Energy Research and Development Administration 3 Agency for International Development 4 National Aeronautics and Space Administration 2 Atomic Energy Commission 1 National Bureau of Standards 1 Department of the Interior 1 Bureau of Reclamation 1 National Park Service 5 Armed Services (Army, Navy)
<u>National Associations</u>	<u>Public Power Interests</u>
<ul style="list-style-type: none"> 4 Sheet Metal and Air Conditioning Contractors' National Association 1 National Association of Homebuilders 1 Air Conditioning Contractors Association 	<ul style="list-style-type: none"> 10 Various Electric Associations 15 Rural Electric Associations 1 Electric Association of France
<u>Research Facilities and/or Corporations</u>	<u>Journalists</u>
<ul style="list-style-type: none"> 13 Universities 4 Westinghouse 3 Copper Development Association 3 Honeywell Research 3 Corning Glass 3 PPG Industries 2 Reynolds Aluminum 2 MITRE Corporation 5 Private solar energy companies 4 Manufacturers, private production 7 Miscellaneous research companies 	<ul style="list-style-type: none"> 8 Representatives of various newspapers, journals, and magazines 5 Television/Radio representatives
<u>Japan</u>	<u>Mexico</u>
<ul style="list-style-type: none"> 18 Researchers representing Japanese companies and universities 	<ul style="list-style-type: none"> 1 Secretary of Education 30 Government officials

Also listed in addition to visitations is a sample of invited talks and presentation of papers by the principal project staff members. These talks and discussions vary from service clubs and schools to professional societies, other universities, and industrial organizations. Table 8 is a partial list of talks, lectures, discussions, and papers presented or participated in by the project staff during the period 1 January 1975 to 30 June 1975.

A primary aspect of this exceptionally heavy research utilization activity has been to limit the available research time. The heavy visitation, while actively demonstrating the potentialities of solar energy, has nevertheless affected the research results by placing unrealistic heating and cooling loads on the installation. These efforts have been minimized to every extent possible by careful management of tours and presentations. The extent, however, of technical visitors to the facility has limited significantly the available research effort in terms of both time and manpower.

Colorado State University has provided considerable funds in order to meet the visitation schedule and requests for information. Appendix D is a sample of handout presently being disseminated to visitors. In addition, approximately 15 letters/week are responded to, without cost to the project, in regard to unsolicited requests for information on solar heating and cooling.

Table 8

Lectures, Talks, and Papers Presented by Principal Project Members
(January 1, 1975 to June 30, 1975)

Date	Presentation	Attendance
Jan. 13	Löf talk before the Energy and Transportation Committee, Colorado House of Representatives	20
Jan. 15	Ward talk before the Colorado Flower Growers Research Committee	10
Jan. 24	Löf talk at the National Association of Homebuilders Annual Convention, Dallas, Texas	400
Jan 24	Löf talk to the Energy Conference, Pueblo, Colorado	150
Feb 5	Löf, Ward, Smith meeting with Governor Lamm and staff at CSU Solar House I, press conference	20
Feb 15	Löf talk at the University of Denver Student Chapter of the National Association of Homebuilders, Solar Energy Conference	250
Feb 18	Löf talk at Solar Energy Seminar, University of Evansville, Evansville, Indiana	30
Feb 18	Löf talk before Tri-State Council of American Society of Mechanical Engineers, Evansville, Indiana	200
Feb 21	Ward talk at Solar Energy Seminar, University of California, Davis, California	50
Feb 23	Löf talk at the Jefferson County Unitarian Church, Denver, Colorado, 2 lectures	80
Feb 25	Löf speech at meeting of Technical Club, St. Mary's Pennsylvania	80
Feb 26	Ward talk at Poudre High School Career Day	20
Feb 27	Ward talk at Fort Collins Sertoma Club breakfast	40
Feb 28	Smith talk to Fort Collins High School Lyceum	40
Feb 28	Löf presentation at Annual Meeting of the Rocky Mountain Science Council, Denver, Colorado	25

Table 8 con't

Date	Presentation	Attendance
Mar 1	Wagner, GRA, talk at Colorado State Teachers Association, Denver, Colorado	90
Mar 5	Löf talk at the Energy Technology Update, Colorado Energy Research Institute, Golden, Colorado	150
Mar 5	Löf presentation at the Special Meeting of the Colorado Section, ASHRAE, Denver, Colorado	200
Mar 11	Löf testimony before the Ways and Means Committee, U.S. House of Representatives, Washington, D.C.	100
Mar 21	Wagner, GRA, talk to Greeley Science Fair, University of Northern Colorado, Greeley, Colorado	50
Mar 23	Smith tour and talk to the Rural Electric Association, Fort Collins, Colorado	25
Mar 25, 26	Smith presentation of paper at the Southeastern Conference on the Application of Solar Energy, University of Alabama at Huntsville, Huntsville	250
Mar 27	Löf and Ward, receipt of Sheet Metal and Air Conditioning Contractors' Nation Association check, presented by Senator Gary Hart	10
Mar 28	Ward talk at the Fort Collins Newcomers Club, Fort Collins	100
Apr 2	Löf talk at the meeting of the Professional Engineers of Colorado, Southern Chapter, Pueblo, Colorado	150
Apr 5	Ward tour of Solar House I with Dr. Alfred Eggers, Director of NSF/RANN	
Apr 5	Smith presentation and meeting with Public Service Company of Colorado	4
Apr 7	Smith talk with the Colorado Division of Wildlife	6
Apr 11	Löf talk at Arizona State University Solar Energy Seminar, Tempe, Arizona	30
Apr 11	Ward talk at the North Carolina State University seminar on solar energy	130
Apr 11	Smith talk at University of Colorado Solar Energy Course, Boulder, Colorado	25

Table 8 con't

Date	Presentation	Attendance
Apr 12	Löf speech at the Annual Meeting, Arizona Section of The American Society of Mechanical Engineers	150
April	4 days, David G. Wagner, Thomas Weiss, and Gail Richardson presentation and demonstration to Larimer County Extension Service course	70
Apr 22	Ward presentation at the Air Pollution Control Association, Air Force Academy, Colorado Springs, Colorado	40
Apr 23	Ward tour and meeting with representatives of the Federal Energy Administration, Denver, Colorado	10
Apr 25	Löf talk before Colorado Alumni, Massachusetts Institute of Technology	100
Apr 28-29	Löf lecture series, presented to the Rocky Mountain Gas Association	30
Apr 30	Smith talk at Alternative Energy Course, Adult Education Program, Colorado State University	20
Apr 30	Löf talk at the Annual Meeting, Board of Directors National Training Fund, Minneapolis, Minnesota	15
Apr 30	Ward talk before Industrial Construction Seminar, Colorado State University	30
May 1	Löf talk to American Institute of Architects, Solar and Energy Conserving Symposium	100
May 1	Löf talk at Initiation Banquet, Sigma Xi Chapter, University of Colorado, Boulder, Colorado	80
May 1	Smith speech to the Lions Club, Fort Collins	50
May 2	Smith talk at the Otero Junior College Engineering Day Banquet, Otero Junior College, LaJunta, Colorado	70
May 5	Löf television interview, sponsored by the University of Colorado	
May 7	Löf talk before the Denver Cashiers Association, Denver, Colorado	
May 8	Löf lecture to Engineering Alumni Meeting, University of Denver, and receipt of Engineering Alumni Award	200

Table 8 con't

Date	Presentation	Attendance
May 13	Smith talk to Loveland Rotary Club, Loveland, Colorado	45
May 13	Löf lecture to meeting of Sheet Metal and Air Conditioning Contractors' National Association, Bermuda	30
May 19	Löf talk at Mechanical Engineering Technology Class, Metropolitan State College, Denver, Colorado	50
May 19, 20	Ward lecture at Colorado Flower Growers Association, in conjunction with CSU Experiment Station, Denver, Colorado	40
May 21	Ward talk at Purdue Agricultural Experiment Station, Purdue, Indiana	50
May 24	Löf lecture at meeting on solar energy at Aspen Institute, Aspen, Colorado	300
May 25	Löf talk at Aspen Institute Workshop, Aspen, Colorado	40
May 27	Löf lecture at Annual Meeting of Public Service Supervisors, Denver, Colorado	60
May 29, 30, 31	Ward lectures at University of Texas Short Course on Solar Energy, Austin, Texas	30
June 2, 3, 4, 5, 6	Solar Energy Applications Laboratory, Colorado State University, hosting of U.S.S.R. solar specialists, Russian Solar Experts Conference	
June 4	Wagner, GRA, talk to Larimer County Cowbells Association Fort Collins, Colorado	40
June 4	Ward talk at Midwest Research Institute, Kansas City, Missouri	270
June 19	Ward presentation of Invited Paper, AAPT-Boulder, Boulder, Colorado	70
In addition to public lectures and presentations, the following instructional contributions were made at short courses in solar energy:		
Feb 12	University of Colorado Short Course, Vail, Colorado	30
Mar 21-22	Solar Short Course, American Institute of Chemical Engineers, Houston, Texas	

Table 8 con't

Date	Presentation	Attendance
Apr 1	Solar Energy Staff Short Course, Marshall Space Flight Center, Huntsville, Alabama	20
Apr 8	Solar Short Course, University of Wisconsin, Madison, Wisconsin	100
Apr 11	Solar Short Course, University of Colorado, Boulder, Colorado	30
May 29	Solar Short Course, University of Texas, Austin, Texas	30

Appendices

Appendix A

Research Contributors

Dr. George O. G. Löf	Principal Investigator
Dr. Dan S. Ward	Project Manager
Dr. John C. Ward	Senior Researcher
Mr. Charles C. Smith	Senior Researcher
Mr. Thomas A. Weiss	Junior Researcher
Mr. David G. Wagner	Junior Researcher
Mr. David Pogany	Junior Researcher
Mr. David M. Frick	Junior Researcher

Appendix B

Reports and Communications on the Project

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SOLAR ENERGY APPLICATIONS LABORATORY AT COLORADO STATE UNIVERSITY

INTRODUCTION

The Solar Energy Applications Laboratory is a center at Colorado State University to conduct research and develop utilization of solar energy for a variety of useful applications. The use of solar energy is certainly not new. In a broad sense, all aspects of life on earth depend upon it. Various life forms have adapted to the low intensity energy from the sun with its seasonal and daily variations. However, mankind has created a need for energy in more concentrated forms, and has for centuries used the concentrated energies in fossil fuels, and in the past few decades in nuclear fuels. With an abundance of these fuels at low cost, there was no economic incentive to develop ways to use solar energy as an additional practical source of power.

As everyone is aware, the cost of fossil fuels has increased significantly over the past few years, and along with this increase, the cost of every manufactured item, including food, has increased in cost. The increasing cost of fuel bills for residences, factories and office buildings and increasing costs for electricity has turned the attention of many concerned individuals, private businesses, and state and federal government agencies, to seek alternative sources of energy.

Solar energy is plentiful, available everywhere and non-polluting. However, it is diffuse and low in temperature. It is variable and requires a storage system to make it available whenever needed. Although sunshine is available for the taking, the taking of it is not free. Along with the economical and technical barriers there is a psychological barrier, the resistance or inertia of the public to adopt new methods and ideas. All three of these factors point to a lead-time necessary to phase in the use of solar energy. The Solar Energy Applications Laboratory at Colorado State University has as its objective in undertaking solar energy research, the technical development for economical application and demonstration of practicality by observing the performance of experimental units.

PRESENT AREAS OF SOLAR ENERGY INVOLVEMENT

Heating and Cooling -- Probably the shortest lead-time needed for application of solar energy is for heating and cooling of space for residences, offices, factories, and warehouses. Indeed, there were only a few residences in the world with solar heating systems before 1973. Now there are scores with promise of thousands more in the next few years. The CSU Solar House I was the first heated and cooled residential-size building in the world and was put into operation in 1974. Although the first system is based on sound technical principles, is reasonably economical in the light of present-day fuel prices and functions well, there is need to develop alternative systems. For this purpose, CSU has constructed two additional solar laboratory buildings to be equipped with solar heating and cooling systems of different designs. Solar House I uses liquid to collect solar energy in the form of heat to operate the components of the system. Solar House II uses heated air, and while Solar House III uses liquid once again, the system is advanced in design to collect solar energy more efficiently than the system installed in Solar House I. With three different systems operating at the same time, under the "same" sun and weather conditions, direct comparisons of the performance of these heating and cooling systems is possible. As new system designs are developed through research, they

can be tested and evaluated using the three solar houses as experimental laboratories.

Reliability of equipment operation is an important question for solar heating and cooling systems. As mentioned earlier, there are only a few systems which existed before 1973, and one important aspect, that of reliability, requires some time before it can be answered properly. However, there is an air heating system, constructed for the residence of Dr. George O. G. Löf in Denver, Colorado, that has been in operation since 1957. The performance of this system was monitored for four years after installation, and after 18 years the system is being evaluated for performance by the staff of the Solar Energy Applications Laboratory. Observations through the 1974-75 heating season indicate that the system provides as much heat now as in the 1958-59 heating season, and the system had no maintenance costs in the intervening years, except for oiling the fan motors and changing air filters, which obviously are normal maintenance practices for any heating system.

Energy conservation, in design and construction of residences, and in practices by its occupants, are important factors in heating and cooling of residences which will be researched by the engineers in the Solar Energy Applications Laboratory. These studies address, not only solar energy conversion technology and economics, but the sensible use of energy delivered by the solar system. The concerns with conservation, conversion and use of solar energy for heating and cooling of space are being actively studied by the staff of the Solar Energy Applications Laboratory.

Solar Thermal Conversion -- The conversion of solar energy to high temperature thermal energy is a subject of study in the Solar Energy Applications Laboratory. Although heating and cooling of space also technically uses thermal energy, a differentiation is made between the low temperatures for heating and cooling and the higher temperatures needed to generate steam to drive a turbine to produce electricity or to be used directly in a manufacturing process.

A study of a wide variety of methods to concentrate solar energy to generate steam is being undertaken. It has been determined that collectors distributed over several acres of land can convert solar energy to steam at high pressure and temperature to drive a conventional steam turbine and generator to produce electricity at a cost that may be competitive with electricity produced from conventional systems. Instead of producing steam at individual collectors and transporting steam over long distances through pipes, an alternative method is to place mirrors over the field replacing the collectors. The mirrors reflect the solar radiation to a "solar boiler" placed high atop a tower which is central to the field of mirrors. Steam is then generated in the solar boiler which is used to drive a turbine and generate electricity.

The system which uses concentrating collectors to generate steam over a large field area is called a distributed system, while the system using mirrors and a central boiler is called a tower/heliostat system. There are many technological problems which need to be addressed preparatory to construction of a pilot solar plant. The staff of the Solar Energy Applications Laboratory will address these problems, along with many other scientists and engineers elsewhere, to seek early application of solar energy for production of electricity.

Other Applications -- Solar energy for agricultural uses is familiar to everyone. Certainly growing crops on open land areas and selected varieties of agricultural products in greenhouses depend upon solar energy. The staff of the Solar Energy Applications Laboratory is, however, interested in using solar energy for other uses on the farm, such as grain drying, heating of animal shelters, and heating water needed for the dairy industry. Although there are no active research projects yet, we expect to initiate studies in the near future.

Conversion of solar energy to electricity without first generating steam, and without using machinery with moving parts, is possible through photovoltaic devices. This is a product of the space age and there are many small systems in operation. Many space satellites have electrical power produced by photovoltaic cells. Terrestrial uses of photovoltaic systems have been limited to small electricity needs in remote locations where it has not been feasible to obtain power from an alternative source. The main reason for lack of widespread use of photovoltaic systems is cost. The cost of electricity from these systems is about 100 times greater than electricity costs available from an electric utility network.

Recent research developments have indicated the possibility of a "breakthrough" in production costs of a photovoltaic device. Much research is still in store before practical systems with reasonable costs can be developed. The future prospects are brighter than they were a few years ago, and is an area where contributions can be made by the Solar Energy Applications Laboratory.

Wind power is a result of solar energy. There is a potential for generating electrical or mechanical power, at favorable sites in various parts of the United States, which may be of service in supplying our energy needs. Site surveys are being made to better assess the potential of wind energy.

Unlike solar energy, wind power has been used for centuries, but has not been exploited to any extent except by the legendary windmills in Holland. There are technical problems that seem to prevent implementation of wind energy to any degree. These problems are deserving of attention and will be addressed by the Solar Energy Applications Laboratory.

ADMINISTRATION AND ASSOCIATE MEMBERS

The Solar Energy Applications Laboratory is operated within the College of Engineering at Colorado State University. The "staff" are faculty of academic

departments within the College of Engineering and the departments of other colleges such as Physics and Economics. The Laboratory is not rigidly structured; it recognizes the diversity of talent among the faculty which is needed in the development of solar energy applications. There is an administrative body for coordinating and organizing the research activity, to assist students and faculty in all departments of the University and agencies, groups and individuals outside the University who are interested in solar energy applications.

Administrative Personnel

Director - Dr. George O. G. Löf, Professor of Civil Engineering
Associate Director - Dr. Susumu Karaki, Professor of Civil Engineering
Assistant Director - Dr. Dan S. Ward, Assistant Professor of Physics

Associate Members of the Laboratory

The members of the Laboratory sometimes termed the "staff" are listed alphabetically below:

William S. Duff - Assistant Professor of Mechanical Engineering
James R. Goodman - Professor of Civil Engineering
Lawrence N. Hadley - Professor of Physics
Ralph W. Hansen - Associate Professor of Agricultural Engineering
Gearold R. Johnson - Assistant Professor of Mechanical Engineering
Thomas B. Jones - Assistant Professor of Electrical Engineering
Susumu Karaki - Professor of Civil Engineering
George O. G. Löf - Professor of Civil Engineering
Robert N. Meroney - Associate Professor of Civil Engineering
Willis W. Shaner - Associate Professor of Mechanical Engineering
Charles C. Smith - Research Associate in Civil Engineering
Sanford B. Thayer - Associate Professor of Mechanical Engineering
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COLORADO STATE UNIVERSITY SOLAR HOUSE 1

In 1973 the Solar Energy Applications Laboratory of Colorado State University received a grant from the National Science Foundation to design, build, and test a practical residential solar heating and cooling system. The primary purpose of the project was to design an effective and economical solar system for heating, cooling, and domestic hot water supply in conjunction with a residential type building, which would be typical in appearance, size, insulation, materials, and energy requirements. The solar heating and cooling system was designed to carry three-fourths of the heating and cooling requirements of the house, and at the same time, maintain a "conventional" level of comfort using a fully automatic control system. The resulting structure is a modern three bedroom house with 3000 square feet of heated space on two levels.

Specifics of house design include:

Total floor area: 3000 square feet
 Floor area, main level: 1500 square feet
 Floor area, lower level: 1500 square feet
 Roof pitch: 45° from horizontal
 Design heating load: 17600 Btu/degree day
 Design cooling load: 26000 Btu/degree day
 Insulation: Ceiling 5 inches fiberglass batt
 Walls 3 1/2 inches fiberglass batt
 Latitude: 41°N
 Longitude: 105°W
 Altitude: 5200 feet

The heating/cooling system in Solar House I can be divided into five basic units: (1) solar collection; (2) solar storage; (3) house heating, cooling, and domestic hot water load requirements; (4) conventional furnace auxiliary system; and (5) automatic controls.

SOLAR COLLECTION

The 768 square-foot flat-plate solar collector is located on the southern roof area at an angle of 45° from horizontal. This orientation of the collectors allows the optimum collection of solar energy during the year.

Ideally a solar collector should face the sun directly. However, in order to accomplish this, the collector would have to follow the sun across the sky. This is impractical on a daily basis, so the collector faces south. The angle the collector makes with the horizontal is also important. For the Fort Collins area, this angle varies with the season (53° for the low winter sun; 37° for the higher summer sun). Again, actual physical movement of the 768 square-foot collector is impractical, even on a seasonal basis. Therefore, a 45° angle was computed as a compromise so that the solar system can minimize the auxiliary annual fuel use. The collector is shown in Figures 1 and 2.

FIGURE 1. CROSS-SECTION SOLAR COLLECTOR

When the collector is in operation, solar energy passing through the cover glasses is absorbed by the metal plate. The heat generated is then transferred to the collector fluid, a 25% solution of ethylene glycol (antifreeze) in water.

FIGURE 2. COLLECTOR TUBE PATTERN

The collector fluid is pumped from the basement into the lower distribution manifold, up through the collectors, and into the upper manifold (Figure 2). From the upper manifold the heated fluid returns to the basement where the heat is transferred to storage (Figure 3).

FIGURE 3. COLLECTOR FLUID FLOW

In order to minimize the amount of ethylene glycol needed, the collector fluid does not pass directly into the storage tank but instead the fluid is piped through a heat exchanger (Figure 4). In this way only about 5 gallons of ethylene glycol are needed. If antifreeze were used throughout the entire liquid system, its cost would be about \$1,000.

FIGURE 4. HEAT EXCHANGER

SOLAR STORAGE

The sizing of solar storage (1100 gallons) is basically an economic decision. While it is possible to provide storage for longer periods of time, additional collectors and storage capacity would be needed. The trade-off, therefore, is the extra cost of solar equipment against the value of the stored energy for the infrequent times when solar energy would be unavailable because of inclement weather. In this area, the occurrence of more than two successive sunless days is not sufficient to justify the extra expense.

HOUSE HEATING AND COOLING

The heat distribution system used in CSU Solar House I is forced air. This choice was predicated on the requirement of heating and cooling, and the availability of commercial cooling units. Operationally, hot water from the solar storage tank is piped to a heating coil or directly to the cooling unit (Figure 5). Air blown across the heating coil picks up the heat to be carried to the house.

For cooling, hot water from the solar storage tank is piped to the air conditioner where it effectively provides the energy to operate the cooling unit. The air conditioning unit is a 3-ton lithium bromide absorption air conditioner, converted for use with hot water instead of natural gas.

DOMESTIC HOT WATER

Besides heating and cooling the house, solar energy is used to provide most of the domestic hot water requirements (Figure 6). Water from a cold water main enters the preheat tank and is circulated through a heat exchanger. Hot water from the solar storage tank transfers heat to the domestic hot water. On demand, water from the preheat tank enters a conventional gas hot water heater which will boost the water temperature (if needed), and maintain the water at the required temperature.

FIGURE 5. HEATING AND COOLING

FIGURE 6. DOMESTIC HOT WATER

AUXILIARY UNITS

During periods of cloudy weather coupled with a high energy demand, the solar units may not be capable of providing all of the heating or cooling. Therefore, a conventional gas-fired hot water boiler is provided to meet the full heating or cooling requirements during these periods. If the temperature in the solar storage tank drops below a predetermined point (100°F for heating; 170°F for cooling), the auxiliary boiler automatically takes over the task of providing heat to the heating coils or the air conditioning unit.

In typical operation, gas provides 20-25% of the heating and cooling load. While it is technically possible to utilize solar energy for 100% of the heating and cooling load requirements, it is economically unsound.

AUTOMATIC CONTROL UNIT

To control the temperature in a conventionally heated home, the homeowner needs only to set the thermostat. The control system for solar heating and cooling is necessarily more complex than a conventional system, since it must control collector and storage pumps and two automatic valves in addition to the more normal functions. The control system installed in Solar House I is fully automatic and capable of controlling all aspects of the units. Setting the thermostat is all the house occupants must do in a solar heated and cooled home.

SOLAR HOUSE II

The Colorado State University Solar House II is similar in physical size, orientation, and thermal characteristics to Solar House I and III. This similarity in design allows for comparative experiments with three different solar energy systems under identical geographical and climatic conditions. For example a direct comparison can be made between the air heating solar system installed in CSU Solar House II and a more typical liquid system in CSU Solar House I.

In the air heating system the collector absorbs solar energy and converts it to heat for space heating and domestic water heating. Circulation is from the solar system to the building in the same manner as most modern heating and air conditioning units but uses air as the medium for heat transfer. The air system is particularly suited for climatic regions where heating loads are high and cooling requirements are moderate. The system utilized in Solar House II operates in either the heating or cooling mode as selected through a seasonal change-over switch. Solar preheated hot water is furnished for domestic use in either mode.

Operational Modes

The building is heated directly from the collector whenever heating is needed during sunny periods, as shown in Figure 1. Air is circulated from one end of the collector to the other with a temperature rise of 50° to 70°F (28-42°C). Cool air from the building is returned to the collector for reheating. The hot water heat exchanger is in series with the collector at all times and provides preheated water whenever the collector is being heated by the sun.

1. HEATING FROM COLLECTOR

The heat storage unit utilizes the heat exchange and heat storage characteristics of dry pebble the most practical storage medium for use with air heating collectors. Solar heated air is routed through the storage unit as in Figure 2, thereby heating the

2. STORING HEAT

pebbles, and the cool air returns to the collector for reheating. Temperature stratification in the storage unit assures maximum heat recovery from the solar air collector. In the evening and nighttime hours, heat is delivered from storage by circulating air from the building as in Figure 3. Because of storage temperature stratification, this mode provides heat at almost the same temperature as from the solar collector. The system automatically provides auxiliary heating from fuel or electricity when solar heat is not available from either the collector or storage.

3. HEATING FROM STORAGE OR AUXILIARY

The evenings and nights are usually cool in Fort Collins. The system is designed to utilize the cool night air during warm summer days by drawing night air through an evaporative cooler and storing the cool air in the pebble bed as depicted in Figure 4. When the living space warms up during the day, air is circulated through the cool storage and to the rooms in the same fashion as depicted for heating (Figure 3). This method of cooling is applicable for areas in the United States where there is significantly cool nights and the air is dry.

4. STORING COOL

Components

The solar system includes: (1) the fixed solar air heating collector having a simple flat absorber and heat exchanger plate, internally manifolded and insulated, of steel construction, and covered by two glass panes; (2) a storage unit with 20 tons (18,200 Kg) of dry pebble bed which accepts solar heated air for winter use or cold night air for summer use; (3) the building space conditioning control unit which includes the sensors and control logic necessary to automatically maintain comfort at all times; (4) the air handling module including air ducts, automatic dampers, filters, and blower; (5) the solar hot water unit consisting of an air-to-water heat exchanger and a preheat storage tank which is connected to an auxiliary hot water heater; (6) a day-night evaporative exchange collar with outdoor air inlet and exhaust duct; and (7) an auxiliary heating unit to provide 100 percent backup space heating when storage temperatures are insufficient to meet demands or when the solar system is not operating.

Acknowledgements

The solar heating and cooling system is a gift to the University by SOLARON Corporation of Denver, Colorado. The auxiliary furnace and dehumidifier have been donated by LENNOX Industries, Inc. of Marshalltown, Iowa. The complete installation is funded by a grant from the Sheet Metal and Air Conditioning Contractors' National Association, Inc. (SMACNA), Washington, D. C.

SOLAR THERMAL ELECTRIC POWER SYSTEMS

A potentially attractive use of solar energy is electric power generation. A large amount of the energy requirements in the United States and the rest of the world is in the form of electricity, so that substantial utilization of solar energy for the production of electricity represents a major savings of conventional fuels.

There have been many attempts to develop practical solar power systems. Experimental and theoretical work has shown promise, but before committing funds toward the construction and testing of expensive pilot plants, the many ways of generating solar thermal energy should be investigated carefully and subjected to economic analysis. The systems which can produce electricity at lowest cost should be identified; first, to determine if the potential for solar thermal power stations is attractive enough to warrant further study, and second, to direct the research and development toward early demonstration of feasibility.

The study of solar thermal power plants was directed to those processes which converted solar energy to heat, and the heat used to drive turbines and generators to produce electricity in ways similar to the way conventional and nuclear fuels are presently used to generate power. Direct conversion of sunlight to electricity through photovoltaic devices was not included in the study, for it appeared that on the basis of economics alone, such devices were 50 to 100 times more expensive than thermal vapor engines.

There are, even by modest categorizing of types, hundreds of possible designs to concentrate solar energy to generate high temperature vapor, and there are scores of possible fluids that could be used to generate vapor to drive, still more, dozens of working engine types and sizes at a variety of speeds to generate electricity. The task is to identify only those systems which, on the basis of performance and costs, have the potential to produce electricity at lowest cost.

Obviously, several thousands of possible systems cannot be designed in detail, to sort out the likely systems. The time required to do this, even with hundreds of engineer-designers, would be endless and when the task is completed, there would be considerable uncertainty about the results because the analysis of performance and cost estimates could not be done on a uniform comparative basis. Thus, a computerized method of design and analysis was used to select a countable few optimized systems for production of electricity through conversion of solar energy to heat.

The two basic types of solar thermal plants are sketched in Figures 1 and 2. The first uses individual concentrating collectors to convert solar energy to steam at the collector, and the steam is accumulated in a network of pipes and delivered at a central site where one large turbine-generator unit produces electricity. The second type reflects solar energy by mirrors to a boiler mounted on top of a tower shown

FIGURE 1. DISTRIBUTED COLLECTOR STATION USING FOCUSING COLLECTORS

FIGURE 2. MULTIPLE TOWER/HELIOSTAT STATION

schematically in Figure 3. A large quantity of steam generated locally on top of the tower is then piped to a turbine-generator to produce electricity. The difference between the two types of systems is in the method of concentrating solar energy. The first system does it by optical and thermal concentration (accumulation of heat in pipes) and the second by optical concentration alone. The boiler is placed on top of the tower so as to be "visible" to mirrors on flat ground surrounding the tower, but alternatively, the mirrors could be on terraced ground, as on a hillside, and the tower could be near the ground.

FIGURE 3. TOWER SUPPORTED ABSORBER AND HEAT EXCHANGER

The results of the system optimization study indicate that both the distributed collector and the tower/heliostat types can potentially produce electricity at costs comparative with conventional fuel systems for a limited time of production during a day. The estimated costs of electricity are shown in Figure 4 for a wide variety of power plant sizes and three steam temperatures.

FIG. 4. IMPACT OF PLANT SIZE AND OPERATING TEMPERATURE ON COST OF ELECTRICAL ENERGY FOR TWO BASIC SYSTEM CONFIGURATIONS

Additional studies are being continued by Colorado State University and Westinghouse to include other possible systems in the analysis. Other groups of engineers in the National Solar Thermal Energy Program directed by the Energy Research and Development Administration (ERDA) are concentrating on the design of tower/heliostat systems. The present goal in the national program is to construct a demonstration power plant in about five years to produce approximately 10 megawatts of electric power.

ECONOMICS OF SOLAR SYSTEMS FOR RESIDENTIAL HEATING AND COOLING

The cost of solar heating and cooling systems for residences includes material and installation costs of the collectors, storage unit, air conditioner and the association piping and controls which connect these components to make up a solar system. The house should be fully ready for occupancy without a solar system. Therefore, costs for ducting, piping and venting for a conventional system should not be charged as cost to the solar system.

The installed cost of a solar collector is presently about \$6 to \$7 per square foot, and this cost can be expected to decline as designs are simplified, material quantity is reduced and manufacturing labor is decreased. The net installed cost of a solar collector should approach \$4 per square foot in the near future. The other components in the system should cost about \$1000 exclusive of the cooling system so that the total solar heating system would cost about \$4000 to \$5000. A typical solar heating system for a modern three-bedroom home can supply about 70 million Btu during the heating season. With a 10 percent annual charge for depreciation and interest, the cost of solar heat is about \$6 to \$7 per million Btu.

If a cheap fuel is available, such as natural gas, solar energy is not yet competitive. However, new natural gas connections are being curtailed in many locations and not available at all in many others. Trends in the prices of three other conventional energy sources are increasing. Fuel oil, presently available at about 40 cents per gallon, is rising. Heat can be supplied for about \$4 per million Btu at oil costs of 40 cents per gallon, but increases to \$6 per million Btu at 60 cents per gallon, a price which it may reach

in the future. At present propane prices, heat costs are near \$6 per million Btu, and with electricity at 3 cents per kilowatt-hour, the cost of heat is nearly \$10 per million Btu. The trends in prices for propane and electricity are also upwards. Clearly, the cost of solar heat is competitive with propane, cheaper than electricity and may be competitive with oil in the future.

The approximate cost of a 3-ton solar operated air cooling unit is \$2000. This cooling unit should be capable of removing approximately 250,000 Btu of heat from the building for seven hours a day at peak capacity using the same solar collector and storage system provided for heating. On a seasonal basis, 100 days of cooling would result in 2000 ton-hours of cooling provided by a solar unit. Amortizing the cost of the air conditioner in 20 years (expected life) at 8 percent, or \$200 annually, the cost of one ton-hour of cooling is approximately 10 cents.

A conventional cooling unit of 3-ton capacity operated by electrical energy requires an investment of about \$1000. The annual cooling load of 2000 ton-hours would require 3000 kilowatt-hours of electricity and, at 3 cents per kilowatt-hour, the electricity cost would be \$90 per year. Adding \$150 annualized cost to the equipment, approximately \$240 per year would provide 2000 ton-hours of cooling. The cost per ton-hour is thus about 12 cents. The cost of cooling with solar energy is thus competitive with conventional cooling costs. Considered from an annual basis, for both heating and cooling, solar energy is competitive with energy obtained from propane and is cheaper than heating and cooling with electricity.

COOLING WITH SOLAR ENERGY

There are a number of alternative methods, using solar heat, to air condition residences. One of the more promising is the absorption system of the type installed and being used in Colorado State University Solar House I. Other types include evaporative coolers, which will be installed in CSU Solar House II, or vapor engines driven by solar generated heat which then drives a compression cooler. Only the basic absorption system is discussed in this leaflet to explain how solar heat is used to cool room air.

It will be easier to understand the basic principle of absorption cooling if we follow the simple diagram below.

The basic components of the system are: (1) generator; (2) condenser; (3) evaporator; and, (4) absorber. The fluid in the system is a solution of refrigerant and absorbent which have a strong chemical affinity for each other. The Arkla-Servel unit in Solar House I uses a lithium bromide-water solution. Lithium bromide is the absorbent and water is the refrigerant.

When the solution in the generator is heated by solar energy (or auxiliary heat if solar heat is not sufficient), the refrigerant (water) is vaporized from the liquid solution. The water boils off (vaporizes at less than 212°F) because the pressure in the generator is lower than normal atmospheric pressure. Heat is removed from the vapor in the condenser, and the vapor changes to a cooled liquid. The cooled liquid is then reevaporized through an expansion valve, and passes into the cooling coils of the evaporator. Vaporization of the refrigerant takes place because the pressure beyond the expansion valve is much lower than the pressure in the condenser.

Warm room air blown over the cooling coil of the evaporator is cooled and the cooled air is circulated back to the rooms. By vaporizing the refrigerant, the temperature is lowered by 50° to 70°F. That is, the temperature of the vapor refrigerant at the evaporator is about 70°F lower than the temperature of the liquid refrigerant, hence it is more effective to cool the room air.

The vaporized refrigerant is next recombined with the absorbent in the absorber. Heat is generated in the recombination, and the heat is removed by cooled

water from the cooling tower. The temperature in the absorber must be sufficiently low to assure a high chemical affinity between the refrigerant and the solution. The solution from the absorber is returned to the generator and the cycle is repeated in a continuous process.

The recuperator (5) shown in the figure is used to cool the high temperature solution in the generator as it passes into the low temperature absorber, and to heat the low temperature absorber solution as it moves to the high temperature generator. This minimizes the heat losses associated with the fluid transfer between the absorber and the generator.

The thermodynamic properties of the "working" fluids in an absorption system are such that the absorber temperature and the concentration of the solution in the absorber determine the pressure in the absorber. The absorber pressure, which is the same as the evaporator pressure, determines the temperature at the evaporator and the amount of effective cooling that can be achieved. The temperature of the condenser determines its pressure, which is the same pressure as the generator. The pressure in the generator and the concentration of the solution determine the temperature needed to vaporize the refrigerant. Thus, the temperature at the absorber and condenser, and the concentration of the solution determine the minimum temperature in the generator. To put it in other words, the temperature of the cooling water achieved by the cooling tower (about 75°F for the system in Solar House I) and the concentration of the refrigerant-absorbent solution, determine the minimum temperature in the generator that has to be supplied by the solar collector before the system will operate (about 180° F for the system in Solar House I). There is also a temperature (generally at the recuperator) for a given concentration of solution in the generator beyond which the system will encounter difficulties because of crystallization (about 120°F for the system in Solar House I).

The solar system in Solar House I operates very satisfactorily. With this explanation of how an absorption system operates, it is easy to understand why the absorption system in Solar House I cannot be used in Solar House II where the air collector is designed to operate at 140°F.

ABSORPTION AIR CONDITIONER--SCHEMATIC DRAWING

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