COO/2858-5

RESIDENTIAL SOLAR HEATING AND COOLING USING AN EVACUATED TUBE SOLAR COLLECTOR

Annual Progress Report, February 1, 1976—March 31, 1977

Dan S. Ward
John C. Ward

April 1977

Work Performed Under Contract No. EY-76-S-02-2858

Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado 80523

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161

Price: Paper Copy $4.00 (domestic)
$6.50 (foreign)
Microfiche $3.00 (domestic)
$4.50 (foreign)

COO/2858-5
Distribution Category UC-59c

RESIDENTIAL SOLAR HEATING AND COOLING USING AN EVACUATED TUBE SOLAR COLLECTOR

Annual Progress Report

for the period February 1, 1976 to March 31, 1977

D.S. WARD and J.C.WARD

April 1977

Under Contract No. E(11-1)-2858

Prepared for

Energy Research and Development Administration
Divison of Solar Energy

Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado 80523

ABSTRACT

During the period 1 February 1976 through 31 March 1977, a residential solar heating and cooling system was designed, installed, and operated in CSU Solar House III. The system consists of 512 square feet of Owens-Illinois (O-I) Evacuated Tube Solar Collector, a 2.2-ton Lithium Bromide absorption cooling unit (Yazaki Corporation), thermal storage units, and associated equipment.

During the installation and initial operation of the system, numerous aspects of the feasibility of this system design have been evaluated. Many of these aspects (described in the section on "Significant Results" and in Appendix A) point to the potentially improved operating performance and long-term durability of a solar air-heating evacuated tube solar collector.

INTRODUCTION

On 1 February 1976, the U.S. Energy Research and Development Administration awarded the Solar Energy Applications Laboratory of Colorado State University a grant to design, install, and test a residential solar heating and cooling system using an evacuated tube solar collector. This report describes the progress of the project during the first fourteen months (1 February 1976 through 31 March 1977).

SCOPE OF INVESTIGATIONS

The objective of the project is to test and evaluate the practicality of an integrated evacuated tube solar collector and absorption cooling system. This is accomplished by designing and installing a complete solar heating and cooling system (including appropriate instrumentation), performing detailed analysis and evaluation of all aspects of the system, and comparing seasonal performances with two other solar heating and cooling systems installed in adjacent buildings with virtually identical thermal characteristics. The two comparison systems, installed in CSU Solar Houses I and II, consist of conventional solar water-heating and solar air-heating flat-plate collectors.

The scope of work during the period of the project covered by this report is limited to the design, installation, and initial evaluation of the solar heating and cooling system. The installation includes the fabrication and installation of the evacuated tube solar collector and the procurement and installation of all components of the solar heating and cooling system. These components include a Lithium Bromide absorption cooling unit, a hot water thermal storage unit, cool storage subsystem, auxiliary boiler, and associated pumps, piping, valves, etcetera.

SIGNIFICANT RESULTS

Project Developments

During the period 1 February 1976 to 31 March 1977, all design work on the complete solar heating and cooling system was completed, including the design of the data acquisition system. A solid-state control instrumentation panel has been designed and fabricated by members of the project staff. Installation of the control panel and interfacing of the control instrumentation and the individual components and sensors of the system (pumps, automatic valves, auxiliary boiler, differential thermostats, etc.) have been completed and all modes of operation have been checked for proper functioning.

All data acquisition equipment and sensors have now been procured, checked for conformance with required specifications, and installed in the solar system. The solar system and building have been provided with a full data acquisition capability, utilizing the existing data logging equipment installed in CSU Solar House II. Initial evaluation of the performance of the installed system has begun with numerous specific experiments being conducted to measure performance of individual components. Examples of such tests are measurements of storage heat loss rates, effects of the boil-off of the collector fluid, and variations in collector performance when using installed reflectors for different collector array configurations.

Numerous developments of significance to the concept of solar heating and cooling have been observed in the design, installation, and operation of the solar system in CSU Solar House III, and in comparing this performance with CSU Solar Houses I and II. These developments are discussed in considerable detail in Appendix A, and are summarized in the section on Technical Developments and Results.

Technical Developments and Results

Significant technical development and results of the project are described in Appendix A. For convenience, a summary is provided here.

(1) Evacuated Tube Design Change - Because of numerous difficulties in leakage and glass breakage of the initial installation of the solar collector array, Owens-Illinois provided (at no additional cost to the project), a complete replacement of all evacuated tube solar collectors and eight new collector manifolds. During the replacement, detailed descriptions and photographs of each of the broken tubes, as well as selected broken glass samples, were provided to Owens-Illinois for further investigation. It should be emphasized that the replacement tubes and manifolds represent a significant improvement in design and long-term performance. Descriptions of previous difficulties with the early design version of the O-I collector must be tempered with performance data on the improved evacuated tubes.

(2) Evacuated Tube Solar Collection Threshold - The theoretical minimum insolation required to operate the solar collector was computed to be 41 Btu/hr·ft^2 (O-I). Experimentally, the minimum insolation required to turn on the collector pump has been observed to be about 50 Btu/hr·ft^2.

(3) Use of Specular Reflectors - The use of specular reflectors attached to evacuated tubes are expected to yield 25 percent more energy than modules with diffuse reflector backgrounds. Tentative experimental results indicate a lower percent improvement. These results are, however, not conclusive.

(4) Electrical Usage - Due to significant pressure drops in the O-I evacuated tube solar collector arrays (4.8 psi at a flow rate of 4.2 gpm), electrical power requirements of the collector and exchanger pumps have been about 0.37 Kw. When combined with space and domestic hot water heating, the power requirements have been observed at a 0.5 Kw level. Solar collection and operation of the space cooling subsystem is expected to require an electrical power level of 0.9 Kw.

(5) Control Sensors - The present O-I solar collector module design does not allow for the insertion of control instrumentation sensors in the

evacuated tube itself and thus severely hampers the control function. It is suggested that any evacuated tube design incorporate a mechanism to allow the insertion of a control or data instrumentation sensor. This would allow for improved control methods, as well as the opportunity to check for good parallel flow distribution in the various collector modules. The present design does not allow for a positive check of the operation of the solar collector array.

(6) Control Time Lag - Because of the low flow rate through the solar collector array (4.2 gpm through sixteen modules), there is an effective time lag from the time when the collector sensor signals a particular temperature until water entering the collector module can reach the outlet of the collector module. This time lag is typically eight to ten minutes. The effect of this time lag on start-up conditions is to increase the outlet temperature by as much as 15°C before the cooler water being pumped into the collector can reach the outlet of each module. This condition greatly increases the chances of an undesirable boiling of the collector on initial start-up. To prevent such an occurrence, a boil protection circuit has been incorporated into the control system to turn on the collector pump whenever it reaches a preset temperature (e.g., 75°C) sufficiently below boiling. While this can prevent boiling of the collector liquid, it decreases the effectiveness of the optimal control functions.

(7) Recommended Design Changes of the O-I Collector - It is recommended that the O-I collector be manufactured as a complete modular unit in order to prevent excessive installation costs. In addition, redesigning the manifold to connect tubes on only one side (with new module dimensions of 4 feet by 4 feet), would provide for several advantages in the initial and continuing operation of the solar collector array.

(8) Collector Liquid - The use of pure water as the collector liquid has been shown to be inadequate because of freezing problems. The addition

of ethylene glycol to the water has prevented freezing, but has other disadvantages. These disadvantages concern themselves principally with the additional difficulty of filling the collectors with the collector liquid mixture and in potential boil off of the collector liquid.

(9) Storage Heat Losses - Heat losses from the thermal storage unit to ambient have been tentatively determined at a value of 46 Btu/hr·°F. At a typical ΔT between storage and ambient of 100°F, this corresponds to 110,400 Btu/day (equivalent to operating the 2.2-ton chiller for two and one-half hours). Heat losses from the domestic hot water preheat and auxiliary tanks represent an additional 54,400 Btu/day.

(10) Potential for Air-Heating Evacuated Tube Solar Collectors - The use of an air-heating evacuated tube solar collector instead of a liquid-heating design would:

(a) Eliminate freezing problems,

(b) Eliminate boiling problems (which are particularly prevalent in evacuated tube collectors),

(c) Eliminate corrosion problems,

(d) Reduce damage to building and system due to leakage problems (although air leaks in an air system would degrade the performance of the solar system),

(e) Eliminate costs of antifreeze mixtures, corrosion inhibitors, and/or exotic liquids used as the collector heat transfer fluid,

(f) Greatly reduce significant storage heat losses, without a heavy cost penalty of greatly improved insulation,

(g) Greatly reduce the problem of insertion of control and/or data sensors in the evacuated tubes,

(h) Eliminate any concern for air pockets occurring in the filling and operation of the collector array (and thus eliminating the use of complete modules for collection of solar energy),

(i) And reduce large pressure drops in the collector array and associated collector/storage heat exchangers.

The only apparent difficulty is the inability of air-heating solar collectors to operate cooling equipment. However, the discussion in Appendix A suggests that evacuated tube, air-heating collectors could, in fact, provide the necessary temperatures to operate Lithium Bromide absorption chillers with or without the use of auxiliary boosting of the solar heated air.

The recommendation for the development of solar air-heating evacuated tube collectors cannot be overemphasized.

COMPLIANCE WITH CONTRACT REQUIREMENTS

The original proposal had anticipated the possibility of obtaining data on the cooling system performance during the latter portion of the 1976 cooling season. This was not possible for several reasons. The original proposal, as submitted, requested a starting date of 1 December 1975, whereas the actual contract award date was 1 February 1976. This two month variance allowed only five months for the final design, procurement of materials and equipment, and installation of the complete system.

Another factor which caused a delay in the initial start-up of the system was the fabrication and delivery of the Lithium Bromide absorption cooling unit from Yazaki Corporation. The fabrication of the unit required an additional month and shipping delays prevented delivery of the unit until August 1976, a shipping time of almost three months.

However, the major factors which have delayed the initial, continuous data procurement from a fully operating system have been the fabrication and installation of the evacuated tube solar collector. Due to administrative difficulties, the purchase agreement between CSU and Owens-Illinois (the evacuated tube solar collector manufacturer) was not consummated until 27 April 1976. At that time Owens-Illinois (O-I) indicated that the required collector components could be fabricated and shipped by 21 June 1976. It was later decided that an improved version would provide significantly better results and better represent the state-of-the-art in this advanced type of collector. Thus a shipping delay of the O-I collectors was authorized and the collectors arrived at Colorado State University in early July.

Plans were then made to install the O-I collector array (utilizing O-I personnel for supervision) during the week of 19 July 1976. All preparations were completed on the subroof, but on 18 July 1976, CSU was notified by O-I that a possible flaw in the collector manifolds had been discovered and a short delay in the installation was requested. However, conflicts with the Winnipeg (ISES) conference and continuing difficulties with the collector manifolds caused additional delays and both collector arrays were not installed in place until early September. Their immediate operation was delayed by a local problem with the final electrical installation and approval. In the interim, leak tests were conducted on all parts of the system (with the exception of the collectors) and the remainder of the system became operational in late September.

Air leak tests on the collector array were then conducted. One interior manifold was replaced (due to internal leakage), and the collectors were filled. After the adjustment of numerous leaking tubes, the system appeared operational. However, two tubes destroyed themselves later that day (probably due to thermal shock), and after discussion with the attendant O-I representative, it was decided that the collector should be allowed to boil off and thus eliminate any trapped air pockets. However, the boiling resulted in the destruction of about fourteen additional tubes. These problems continued and, over a period of several weeks, almost forty tubes required replacement.

Numerous design changes were made to correct for several of the difficulties encountered, principally due to partial draining of the collectors and destructive thermal shock to the tube when refilled. In early November, O-I suspected inferior quality glass and agreed to replace all the collector tubes with their latest model (at no additional cost to the project).

In addition, O-I provided specially designed reflectors which were considered to be an additional improvement in the collector array subsystem.

The entire array of collector tubes was removed in late November and by 5 December, all collector tubes, including reflectors, were installed in the upper collector array (the upper half of the complete collector array). Thereafter extensive tests were conducted to ensure the capability of the upper array replacement tubes to withstand boiling conditions. When these tests were successful, plans were made to install the lower array and complete the installation. Due to inclement weather, the installation was delayed until the first week in January.

With the entire collector array installed, attempts were made to fill the system. However, numerous leaks in the manifolds of the lower array (due, apparently, to freeze damage) necessitated the removal of the complete lower array (including all tubes). In the interim the upper array was filled with a water-ethylene glycol mixture (previous freezing problems had demonstrated the necessity of antifreeze), and the system was put into operation utilizing only the upper array. Leaks in the lower manifolds were due to bursting pipes from freezing, caused by incomplete drainage of the lower manifold pipe. Replacement manifolds were provided by O-I in February and the complete solar collector array became operational in late February 1977.

During the months of January and February, acquisition of performance data was recorded for the purpose of checking out and testing the data acquisition equipment. After several modifications to improve the data acquisition characteristics, continuous monitoring of performance data (including periods of specialized tests on the system) was begun on 1 March 1977. A computer routine to analyze the accumulated data has been prepared, tested, and is now operational.

At the present time final check-out of the cooling subsystem is being conducted. It is anticipated that continuous data collection on the performance of the solar cooling subsystem will commence on 1 June 1977. A request for renewal of the contract will provide for a full cooling season test of the installed equipment. In addition, a full heating season test, with some potential modifications to the system (to be installed in October 1977) will be conducted during the winter of 1977 - 1978.

PERCENTAGE OF TIME OR EFFORT OF PRINCIPAL INVESTIGATOR

During the period 1 February 1976 to 31 March 1977, the principal investigator devoted approximately 60 percent of his time to the project. It is anticipated that he will devote 88 percent of his time for the remainder of the project (from 1 April 1977 through 31 July 1977).

TECHNICAL PUBLICATIONS

Technical publications arising as a result of the project include:

1. (COO-2858-1) "Cooling Subsystem Design in CSU Solar House III", D. Ward, T. Uesaki, and G.O.G. Löf. Presented at the International Solar Energy Society conference, Winnipeg, Canada, August 1976.

2. (COO-2858-2) "Cooling Subsystem Design in CSU Solar House III", D. Ward, T. Uesaki, and G.O.G. Löf. To be published in Solar Energy Journal, Vol. 19, 1977.

3. (COO-2858-3), "Design Considerations for Residential Solar Heating and Cooling Systems Utilizing Evacuated Tube Solar Collectors", D.S. Ward and J.C. Ward. To be presented at the International Solar Energy Society Conference, Orlando, Florida, June 1977.

4. (COO-2858-4), "Design Considerations for Residential Solar Heating and Cooling Systems Utilizing Evacuated Tube Solar Collectors", D.S. Ward and J.C. Ward, To be submitted to Solar Energy Journal, May 1977.

5. (COO-2858-6) "A Performance Comparision Between Air and Liquid Solar Residential Heating Systems", S. Karaki, W.S. Duff, G.O.G. Löf, and D.S. Ward. To be presented at the International Solar Energy Society Conference, Orlando, Florida, June 1977.

APPENDIX A
SIGNIFICANT DEVELOPMENTS

Considerable information has been acquired in the course of installing and operating the solar heating and cooling system in CSU Solar House III, utilizing the Owens-Illinois (O-I) evacuated tube solar collector. One particularly important aspect of the project has been the replacement of the complete solar collector array with an improved design. Because of numerous difficulties with the initial set of O-I evacuated tubes and manifolds (broken and leaking tubes, freeze burst manifolds, etc.), O-I furnished a complete replacement of all evacuated tubes and eight new manifolds. It should be emphasized that most of the difficulties experienced in glass breakage (discussed below) occurred with the initial collector array. The replacement array has proven to be of a much higher quality and relatively few difficulties have been encountered since their installation in December, 1976 and January, 1977.

INSTALLATION

EVACUATED TUBE COLLECTOR ARRAY

On-Site Assembly

Figure 1 shows the components of a single 4 foot by 8 foot collector module of the O-I design. The actual assembly of all the components on site (generally a steeply sloping roof) is time consuming and requires careful attention to detail. The parts list for a single module consists of about three hundred separate pieces; thus the CSU Solar House III sixteen module array consists of about 4,800 pieces. While many of these components can be assembled on the ground (e.g., 12 grommets, 24 O-rings, and 24 end seals can

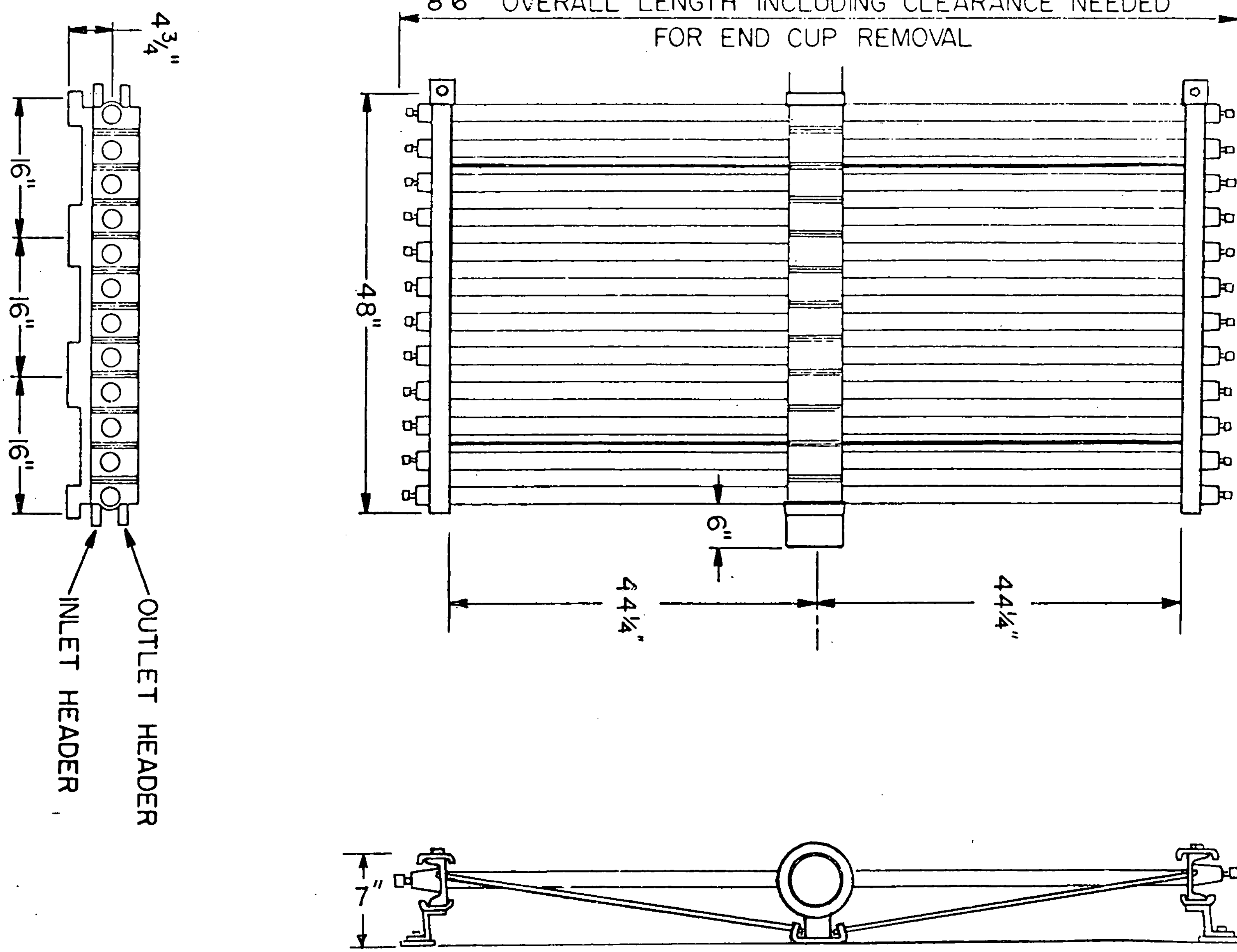

8'6" OVERALL LENGTH INCLUDING CLEARANCE NEEDED
FOR END CUP REMOVAL
48"
6"
44¼"
44¼"
7"
4¾"
16"
16"
16"
INLET HEADER
OUTLET HEADER

Figure 1

be installed in the manifold), others require individual attention. For example, the tube support cup assemblies consist of five pieces which can be preassembled, but have a tendency to fall apart prior to actual installation. Such features slow the installation process considerably. If reflectors are added to the above list, this constitutes twenty-four reflectors and 96 wire clips per module. The wire clips are particularly hard to work with and in cold weather require workmen to work without gloves. The effect of this multitude of pieces (about 6,700 total) is to greatly increase the cost of installation, and would suggest that a self-contained modular design that could be lowered into place as a single unit would be much preferable.

In this regard it should be noted that the dimensions are critical and must be laid out on the roof with great care. For example, the distance between the center line of the manifold and the end bracket must be exactly 44-1/4 inches, in order for the evacuated tubes to be able to fit in the space. But, in addition to the difficulty of laying out this dimension and maintaining a perfect square, one must also contend with the tendency of the manifolds and end brackets to lean toward the down slope of the roof (a factor more noteworthy whenever an installer inadvertently uses the manifold as a foot hold.)

Finally, the collector module requires an additional six inches for an overall length of 8' 6" in order to provide sufficient clearance for end cup removal. In reality even more area between collector arrays is needed in order to provide working space during the actual assembly (and avoid putting weight on the manifolds or end brackets). This additional area must then be charged to the total collector area; the required area for two arrays of eight modules each might then be a space of 32 feet by 18 feet, or 576 square feet (instead of 512 square feet); of which 438 square feet is reflector, 234 square feet is tube, and 181 square feet is absorber tube area.

Leakage Problems

A principal difficulty with an on-site assembly of the solar collector modules is the inability to check for potential leaks until the entire collector has been installed. Once a leak is discovered, a large portion of the complete array of tubes must be removed in order to repair the leak. And, in the process of removing tubes, this can damage other components. For example, because the collector usually sits in a no flow, dry condition prior to initial start up, the rubber connectors for the feeder tubes are effectively baked on the feeder tube. In the process of removing the collector tubes to repair a leak, these rubber connectors must be cut and then replaced with new ones upon reassembly. The collector manufacturer has recognized this problem and is now considering alternate materials for the feeder tubes connectors.

Substantial leaks have occurred in the connections between the manifolds and at the junction of the evacuated tubes and the manifold. The latter source of leaking is relatively easy to correct and usually requires only an adjustment of the tube in the manifold cup. The only difficulty arises when an upper tube must be adjusted. In this case it is easy to dump the collector liquid during the adjustment and thus introduce a large air pocket into the module. This is not self-correcting and it may be necessary to drain the entire collector array in order to correct the situation. (The draining of the collector array is discussed below.)

Significant leaks in the manifold connections are generally more difficult to correct, and in the case of the first O-I design, were more common. The first design required soldering of one inch copper pipes (two per interface between manifolds). Normally two manifolds are soldered together on the ground and then placed on the roof as a unit. This proved completely unsatisfactory, as the subsequent movement stressed the solder joint to the extent that five out of eight connections made in this way developed leaks. Ironically, no soldering work performed on the roof to connect the manifolds had any leaks at all. O-I has since replaced the requirement of copper pipe soldering with specially adapted fittings. These fittings enormously simplify the installation on a roof and are a decided improvement. In the CSU installation, the lower array utilizes the improved fittings while the upper array uses the earlier soldering technique.

The difficulties associated with being able to check for leaks in the collector manifold assembly and the related piping, prior to the completion of the array's installation is compounded by the inability to easily drain the collector to an extent which would allow repairs to be made and to subsequently recommence operations. On the other hand, the upper tube on either side of each collector module will self-drain unless specific precautions are taken to prevent this. (In fact, it was necessary in the CSU installation to incorporate a piping loop on the outlet of the collector which could provide back pressure greater than the water head to prevent an unwanted drain down.) Unfortunately, the self-draining is a very slow and lengthy process. In one case where a copper solder joint on the inlet side of the collector (the piping leading to the collector) developed a leak, it was necessary to drain the collector inlet in order to repair it. (It is extremely difficult to repair a solder leak when there is any water in the pipe, as the heat goes toward boiling the water rather than heating the copper pipe.) Because of the slow self-draining, it took three days for the tubes to drain to the extent that repair was possible.

It is, of course, possible to drain the system in a more positive manner. One method is to pull all upper tubes out of the manifold, thereby dumping the collector liquid onto the roof. This is a difficult, lengthy, and somewhat hazardous procedure due to the normally high temperatures of the collector liquid (note that, once the collector flow rate was shut off, the time to empty all tubes in an array could easily allow the last tubes to be boiling by the time they were attended to.) While the lower tubes would not have to be emptied in order to repair the leak, they will have to be emptied in order to assure proper refilling (with no air pockets) and subsequent normal operation. Thus this method of draining is time consuming and quite laborious.

A simpler method is to allow the collector tubes to boil the collector liquid until dry. One disadvantage is the loss of any collector liquid or additive other than water (e.g., ethylene glycol). Another disadvantage is the time (again, several days) to complete the process. There is also the disadvantage of possible damage to the collector due to boil off (see below -- Operational Results). In addition, the collector manufacturer no longer considers such intentional boil off as an acceptable procedure.

The difficulties encountered in draining a collector module and in other aspects of the operation of the collector would suggest a modified design. Either of two alternatives is a possibility. One is to design the manifold such that all tubes are below the manifold (the dimensions of the module would then be approximately 4 foot by 4 foot). This has the advantages of no self-draining, ease in removal with minimum loss of collector liquid, and a simpler design. Alternatively, the tubes could be placed above the manifold (again a 4 foot by 4 foot module). This could allow for an automatic drain down system and would simplify the problem of air bubbles trapped in the collector tubes. The essential problem with the present design is the combination of tubes above and below the manifold. Such a combination nullifies many of the advantages of either case and increases the possible disadvantages of both cases.

Pressure Drops

The pressure drop across an O-I collector module is dependent upon the flow rate and has been given by O-I in the form:

Flow Rate (gpm)	Flow Rate (lbs/hr·ft²)	Pressure Drop (psi)
0.11	2.0	1.0
0.22	4.0	3.5
0.33	6.0	7.0
0.44	8.0	13.0

The CSU installation has a flow rate for 16 modules (in two parallel arrays of eight modules each) of 4.2 gpm (0.26 gpm/module), which would correspond to a pressure drop of about 4.8 psi. The collector pump is a Bell and Gossett Series 60, one-half horsepower pump, designed for a flow rate of 4.0 gpm against a total pressure drop in the collector loop of 15.1 psi. This large pressure drop is due primarily to the pressure drops across the heat exchanger between the collector loop and storage and the O-I collector array. For only one array in the collector loop, the same pump provides for a flow rate of 2.6 gpm (indicating a pressure drop across the eight collector modules of 7.0 psi). Addition of ethylene glycol increases the pressure drops.

These high pressure drops constitute a severe disadvantage of the evacuated tube solar collector because of the potentially high pumping power required. In the case of CSU Solar House I, for example, the Corning collector utilizes a 1.5 horsepower pump in the collector loop. While the collecting and cooling equipment were both in operation, power requirements totaled 53.5 amps at 115 volts, or 6.152 kilowatts. A conventional vapor-compression machine of the same capacity (3-tons) might require only 4 to 5 kilowatts.

Tentative information on the O-I collector and the CSU Solar House III system indicates that electrical usage for collection and storing of solar and subsequent distribution of heat to the space heating load has a power requirement of approximately 0.5 kilowatt. For the collection of solar heat and the operation of the cooling subsystem to extract heat from the building, the power requirements are expected to be 0.9 kilowatt. Thus it is imperative that any abnormal pressure drops across a solar collector or other component be minimized.

In addition, the pressure drop across the O-I collector has been observed to be slightly higher when filling the system. In fact, the one-half horsepower pump described above was unable to fill the system without the back pressure of a head of water from the collector outlet to the pump of about 20 feet of water head. While the DHW pressurized water main has been suggested as a simple means of filling the collector, such a tactic is severely limited if it is desired to add ethylene glycol for freeze protection or utilize some other liquid as the collector fluid.

It should be noted that O-I has the option of installing enlarged feeder tubes, which significantly reduce the pressure drops across a collector module.

Control Instrumentation

The collector pump is controlled by a differential thermostat between the collector and the thermal storage unit. However, the O-I design of the evacuated tube collector module does not allow for the insertion of a sensor which can measure directly the collector fluid temperature. While the outlet of the collector array could be used, this gives a substantially different reading when there is no flow in the collector itself (in many cases, exceeding a difference of 10°C). Thus, unless the collector fluid temperature is directly measured, the ability of the control system to optimally control the collector pump is severely degraded.

In the CSU installation, a control sensor was placed in the last tube of one module and the wiring was run through the manifold piping to a connection on the collector outlet pipe. This was a difficult procedure and, ideally, should not be necessary. In addition, because of numerous boil offs and exceptionally high stagnation temperatures, the sensor has required periodic replacement. Such replacement could be greatly facilitated by a specific design feature to allow for easy insertion of control or monitoring instrumentation. (It should be noted that most control sensors require a larger voltage output than is available from thermocouples.)

The provision for the insertion of a temperature sensor in one tube of each module would also allow for a check of adequate flow to all modules piped in a parallel flow. On several occasions at CSU, when the collector had been operating, it was necessary to shut down. To prevent boil off and any possible damage to the collector tubes, the tubes were manually removed and emptied. In the process, six tubes in the upper array were discovered which were dry inside, indicating no flow prior to the shut down of the collector pump. A check of the data indicated no detectable change in the flow rate previous to that time. Therefore such temperature sensors would be deemed essential in order to adequately check out the initial operation of the system.

SOLAR HEATING AND COOLING SYSTEM

Equipment

The installation of the remaining components of the solar heating and cooling system was accomplished without major difficulty. However, the fact that the house was completed and occupied, complicated the installation and the effort became essentially that of a retrofit (although the collector area had already been provided for). The major difficulty was in the small area allotted the solar equipment, which included a 1200 gallon horizontal cylindrical storage tank, two 500 gallon cool storage tanks, one 82 gallon and one 42 gallon hot water tanks, an absorption chiller, an auxiliary boiler, and numerous pumps, heat exchangers, and associated piping.

One particularly difficult area was in the small space between the return air duct and supply air plenum chamber. It was necessary to place two large liquid-to-air heat exchangers plus a house distribution blower in a space measuring less than five feet along the air flow path. This caused the problem of placing the blower too near the building's return air inlet and, consequently, produced an unacceptable noise level. This was eventually compensated for by the relocation of the building's return air inlet.

Control Instrumentation

The control instrumentation system was developed by a member of the project staff and utilizes a completely solid-state control design. This system has proven to be reliable, relatively inexpensive, and highly versatile in the incorporation of design changes and in providing additional data information on the status of the system.

OPERATIONAL RESULTS

COLLECTOR OPERATING CHARACTERISTICS

Freezing

It might be expected that the evacuated tube solar collectors can resist freezing because of their extremely low heat loss coefficient. This is true to some extent, although after several days (three or more) of very cold weather conditions and minimal solar input, the water-filled tubes may freeze and shatter the evacuated collector tube. However, because of the much greater danger of freezing in the piping and manifolds, it is not considered feasible to use water as the collector liquid without additional freeze protection steps being incorporated.

In the CSU installation, freezing in the piping leading to and from the collector array occured on two separate occasions in November 1976. In January 1977, the lower collector array manifold froze and burst the lower manifold pipe in five places. In this case the collector tubes were not in place, and the lower manifold pipe had failed to drain. Because of these experiences, the collector liquid now consists of a 25 percent ethylene glycol (by volume) aqueous solution. It is anticipated that this will be replaced during the cooling season for an all-water system, in an effort to evaluate the effects on the performance of the system due to using an ethylene glycol solution rather than water.

Boiling

In the initial installation of the O-I collectors on CSU Solar House III, numerous leaks between the evacuated tubes and the collector manifolds required a shut down of the filling process. Subsequently it was decided to allow the collector to boil off any remaining liquid, with plans to refill the system at a later date. On the same day, two tubes destroyed themselves due to what is now believed to have been thermal shock. On the following day, approximately eighteen additional tubes were destroyed before the entire collector array was covered.

The destruction of the tubes took two forms. The first occurred at the juncture of the absorber tube and the outer tube, i.e., the "neck". The second type of breakage was at the opposite end of the absorber tube and was caused either by the inner feeder tube or the coiled spring separating the absorber tube from the outer tube. While the absorber tube was destroyed or broken in every case, the outer tube was broken in about half the cases, with no correlation as to how the absorber tube was destroyed.

Similar breakage was also observed during filling of the collector. For example, in November 1976, project staff began filling the collector at 9:00 A.M. Because the low flow rate implies a total filling time of about twenty minutes, the last tubes in each module (there are 24 tubes in series for each module) continued to heat up until, at 9:15 A.M., several tubes near the outlet of each manifold had developed significantly higher temperatures. When the cooler water entered the hot tube, the absorber tubes destroyed themselves.

It should be stressed, however, that while the initial collector installation had numerous and continuing glass breakage problems, the replacement evacuated tubes supplied by O-I, at no additional cost to the project, have performed satisfactorily. In a test of the ability of the tubes to withstand a boil off condition, all tubes with the exception of one were apparently undamaged. The single exception developed a leak between the tube and manifold and required subsequent replacement. At a later date, a failure of a flow meter interrupted the normal flow and caused an inadvertent boil off condition. In this case the pressure reliefs were automatically actuated and the entire collector array underwent no apparent damage.

The replacement evacuated tubes appear to be a substantial improvement. During the initial filling of the new tubes, virtually no leaks between the tubes and manifolds developed; a decided improvement over the earlier tube design version. In addition, the new support between the absorber and outer tubes is a much more positive support and indications are that the design change was particularly useful. The new tubes also have a getter, which now provides for direct indication of a loss of vacuum in the evacuated portion of the tube. Unfortunately, once the tube is installed, the getter is covered by the end cap and hidden from view; thus denying the ease in which the collector tubes can be checked for vacuum.

Finally, the apparent improvement in the consistency of the absorber's selective surface was noted during the installation of the replacement tubes -- the older tubes appeared to have a wide variation in coloring, approaching the appearance of a rainbow. However, since the installation of the replacement tubes, some indication of the collector surface toward the rainbow color has been observed, but it is not known as to what degree this aspect in optical properties affects the thermal performance of the collector; or whether or not there has been a change in the optical properties of any one tube.

Time Lag

Because of the high pressure drops and subsequent low flow rates through the solar collector array, there is a time lag between the time the collector liquid enters the first tube of a module until it exits from the last tube of the same module. In normal operations this time lag has a duration of about 8 to 10 minutes, although during filling operations of one collector array at a time, the time lag varies from 15 to 20 minutes. Table 1 gives the temperatures of the collector and thermal storage, as well as the collector flow rate, with respect to time for one typical start up. (The collector pump is first energized at 0844 MST; 16 March data.)

Table 1. Collector Start Up Temperatures

Time	Storage Temperature (°C)	Collector Outlet Temperature (°C)	Collector Flow Rate (gpm)
0844	60.5	68.0	---
0845	60.8	68.5	3.9
0846	61.2	69.0	3.5
0847	61.6	69.3	3.5
0848	62.4	69.9	3.4
0849	62.6	74.9	3.4
0850	62.3	77.5	3.1
0851	62.5	81.8	3.3
0852	62.3	82.4	3.7
0853	62.1	78.7	3.9
0854	62.1	74.8	3.8
0855	62.0	72.2	4.0
0856	62.2	70.7	3.9
0857	61.9	69.9	4.0
0858	61.7	69.2	4.1
0859	61.5	68.9	4.2
0900	61.4	68.6	4.3

It is noteworthy that the collector temperature rises for about eight minutes until the cooler inlet water reaches the temperature sensor in the outlet tube. The temperature rise over this time period (early in the morning) is 14.4°C. At higher initial temperatures the rise is slightly less (e.g., 76.9°C to 89.8°C for a rise of 12.9°C). Obviously, such a ΔT raises questions as to the validity of such a control system for the collector pump. While the temperature of the collector does return to the region of the initial temperature in each case, there is the distinct possibility of boiling the collector before the temperature rise can be halted.

For example, in the Fort Collins area, the boiling point of water is 95°C. The absorption chiller is designed for temperatures of 80°C. Thus storage on a summer morning can be expected to be no lower than 80°C less any heat losses overnight (about 2°C drop). If the collector/storage temperature differential to turn the collector pump on is 7°C, then the collector pump will turn on when the temperature of the collector reaches 85°C. If the expected temperature rise is 11 or 12°C, the collector temperature will then reach the boiling temperature before the cooler inlet water is available at the last few tubes of each module. Thus the collector begins to boil.

The collector/storage differential can be lowered and the absorption chiller can be operated at temperatures as low as 75°C, so that this problem can be reduced, in principle. The addition of ethylene glycol will also raise the local boiling point (a 25 percent solution has a boiling point of 102°C in the Fort Collins area), which will ease the difficulty even more. Nevertheless, the problem is likely to persist whenever the storage temperature is high, reflecting an abundance of solar radiation and a lighter cooling load. Because of this potential difficulty, the control instrumentation was modified to provide boil protection by turning on the collector pump whenever the collector temperature reaches a preset value (e.g., 75°C), irrespective of the temperature in storage. (The modification eliminated a similar freeze protection mode which, with a glycol-water mixture for collector fluid, was no longer needed.) Unfortunately, this modification is expected to degrade any optimal control strategy.

Collector Fluid Considerations

The 1977 winter heating season in the Fort Collins area has been comparatively mild (about 20 percent fewer heating degree days than normal). The combination of lower heating loads and the high collector temperatures easily obtained by the O-I evacuated tube solar collectors provides for a high degree of probability that some boiling will occur in the solar collector over the course of a year. This is particularly true in the spring and fall, when heating/cooling loads may be nonexistant, and solar radiation on a 45 degree tilt will be at a maximum.

Several alternatives exist to counter this undesirable condition. The collector array could be undersized for the particular building load and storage could be oversized to account for the spring and fall excess energy. However, any oversizing of storage would have to consider the effects on its ability to meet the temperature requirements of the absorption chiller. A multiple storage tank facility could be utilized to avoid this problem, but only at a cost of greater complexity.

An alternative possibility is the use of covers for the collector to prevent boil off. This, again, would mean higher costs and greater complexity without any significant improvement in the performance of the solar system.

The simpler and more desirable alternative is to eliminate the problem altogether by eliminating water as a constituent of the collector fluid. This can be done by the use of a low freezing point-high boiling point heat transfer liquid, or by redesigning the evacuated tube solar collector to use air as the collector heat transfer fluid. Liquids exhibiting the necessary characteristics have been detailed in reference 1, and might include butyl benzyl phthalate (Freeze, -31°F; Boil, 698°F) and diethyl o-phthalate (Freeze, -41°F; Boil 568°F).

Modification of the evacuated tube solar collectors to utilize air as the heat transfer fluid would have numerous advantages. All difficulties of freezing, boiling, corrosion, and costs of exotic liquids would be eliminated. In addition, the thermal performance of solar air-heating systems have been shown to be slightly better than solar water heating systems using flat-plate collectors. The only potential disadvantage of a solar air-heating collector has been its inability to obtain temperatures high enough to operate solar cooling machines.

However, an evacuated tube solar air-heating collector would nullify this problem. While a normal air-heating flat-plate collector and pebble-bed storage would operate with temperatures of 70°F (outlet of storage and inlet of collector) and 140°F (outlet of collector and inlet of storage), an evacuated tube could "leap frog" this range of temperatures during the cooling season and operate at temperatures of 140°F and 190° to 200°F (respectively). Figure 2 shows a schematic of a potential solar air-heating collector heating and cooling system. Figure 3 shows the absorption water chiller subsystem which could be used with the system shown in Figure 2. It should be pointed out that both Owens-Illinois and General Electric are presently developing commercial solar air-heating evacuated tube solar collectors.

EXPERIMENTS

Thermal Storage Heat Loss

Experiments have been conducted to determine the heat loss characteristics of the thermal storage unit, as well as the domestic hot water (DHW) preheat

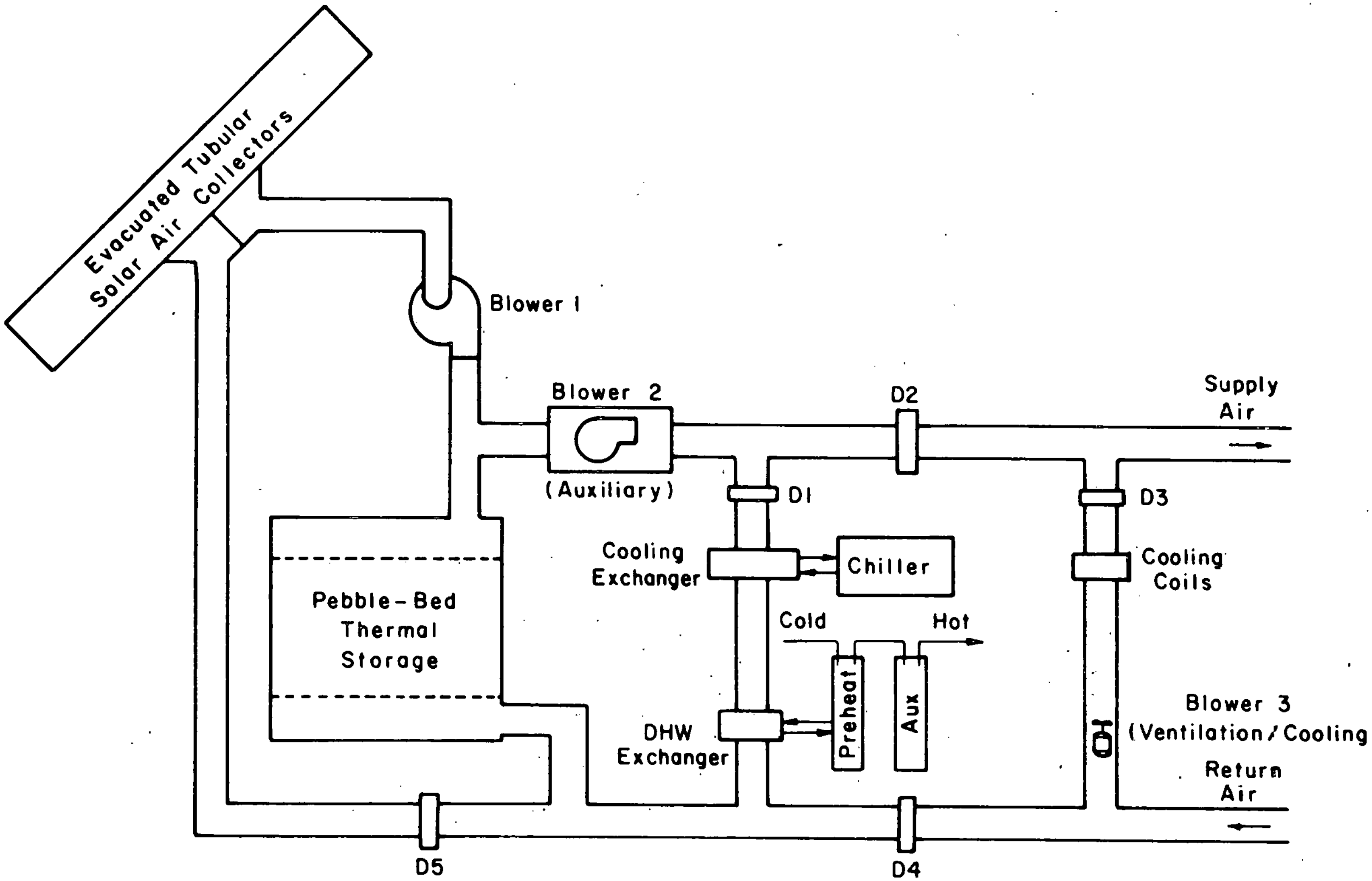


Figure 2. Solar Air-Heating and Cooling Subsystem

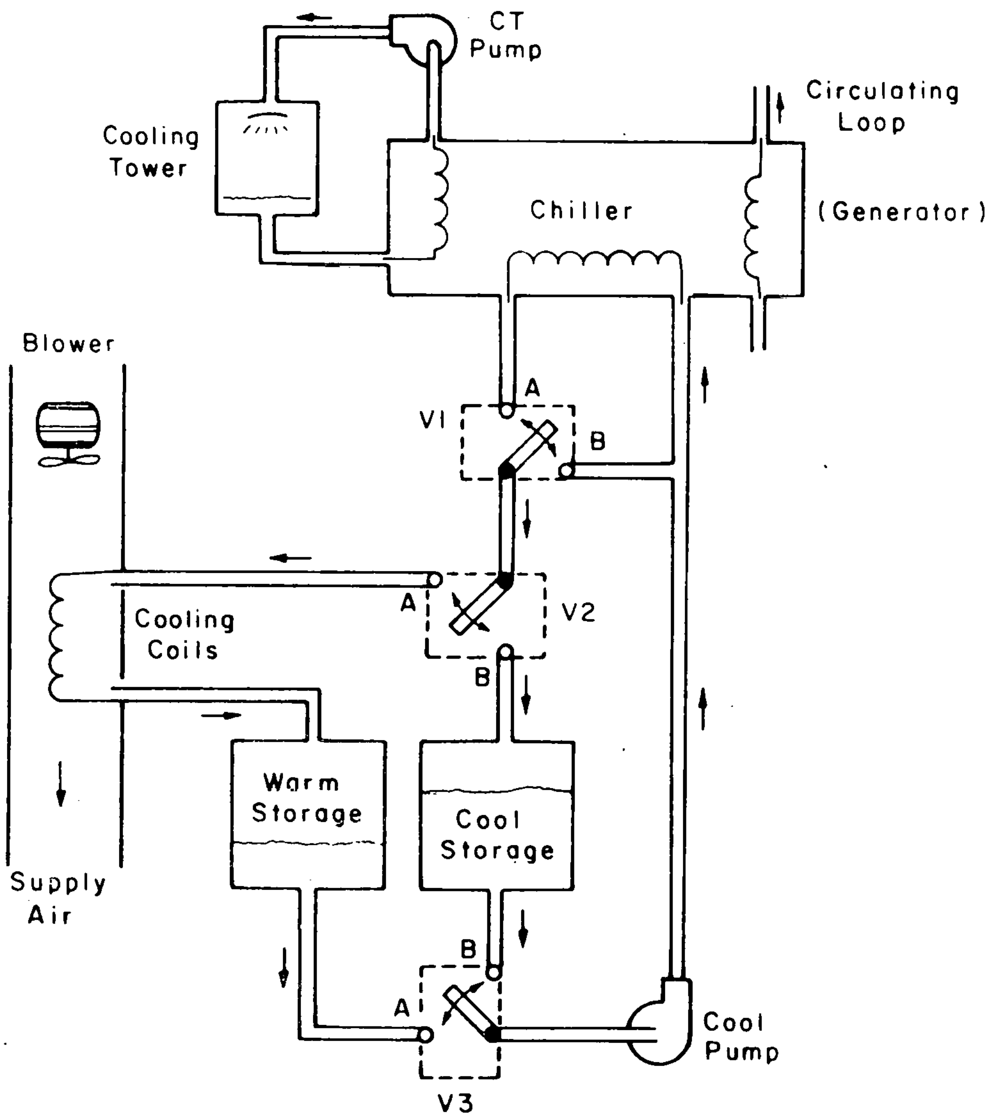


Figure 3. Solar Cooling Subsystem

tank and the auxiliary (electric) DHW tank. The results are shown in Table 2.

Table 2. Tentative Storage Heat Loss Results

Component	Overall Heat Loss* (Btu/hr·°F)	Heat Loss Coefficient* (Btu/hr·ft^2·°F)
Thermal Storage	34.7	0.218
DHW Preheat	9.36	0.242
DHW Auxiliary	7.75	0.311

*Based on the temperature difference between the stored hot water and the temperature of the insulated equipment space

These heat loss characteristics amount to a daily total heat loss of approximately 46,000 Btu/day. This corresponds to two hours of chiller operation to overcome the additional cooling load due to heat losses from the solar equipment. However, provisions have been made to partially disassociate the equipment space from the building and thus significantly reduce the effects of these storage heat losses on the building's cooling load.

However, this provision exposes the thermal storage units to ambient temperatures. Initial results show an overall heat loss for the 1200 gallon thermal storage unit of 46 Btu/hr·°F. For a typical ΔT between storage and ambient of 100°F, this corresponds to a heat loss of 4,600 Btu/hr. Even if this heat loss does not add to the building's cooling load, it does represent waste heat that is no longer available for use. Such an amount of waste heat would correspond to 110,400 Btu/day, or the ability to operate the 2.2-ton absorption chiller for two and one-half hours.

It is anticipated that future efforts would be to reinsulate the hot water storage tanks with additional and/or improved insulation materials. However, it is not expected that the large heat loss rates can be reduced significantly and, therefore, such heat losses must be considered as a characteristic of liquid systems.

Reflectors

The initial design of the O-I evacuated tube solar collector module called for a white reflective surface (as part of the roof structure) to be located directly behind the evacuated tubes. A modification to this design is the use of a shaped, specular reflector, directly behind and attached to the evacuated tubes. O-I expects the collector module equipped with these reflectors to yield over 25 percent more energy than a similar module using a diffuse reflector.

The installation at CSU Solar House III has the specular reflectors installed with the solar collector upper array, but is still utilizing the diffuse, white background reflector on the lower array. Tentative results indicate a lower percent improvement of the specular reflectors over the diffuse surface over the period of one day. Figures 4, 5, and 6 show initial raw data plots. On 16 March 1977, (Figure 4), the array with specular reflectors (upper array denoted by the temperature, $T_{o,u}$) showed an approximate 17 percent improvement. Note, however, that from 1200 to 1500 the percent improvement was about 40 percent. On 19 March, 1977, (Figure 5), we see virtually no improvement due to the reflectors.

The above tentative results are based on the assumption of equal flow through the upper and lower manifolds. This is by no means assured and, as can be seen in Figure 6, the upper array has boiled and has virtually no flow. Future efforts will address the problem of ensuring equal flow rates to the two arrays. Until then, the results indicated in Figures 4 and 5 must be considered tentative.

Collector Threshold

According to Owens-Illinois (2), the O-I evacuated tube solar collector has a threshold of 25.4 Btu/hr·ft^2 (beam) (i.e., the minimum insolation required to operate the solar collector). This correspond to a total radiation

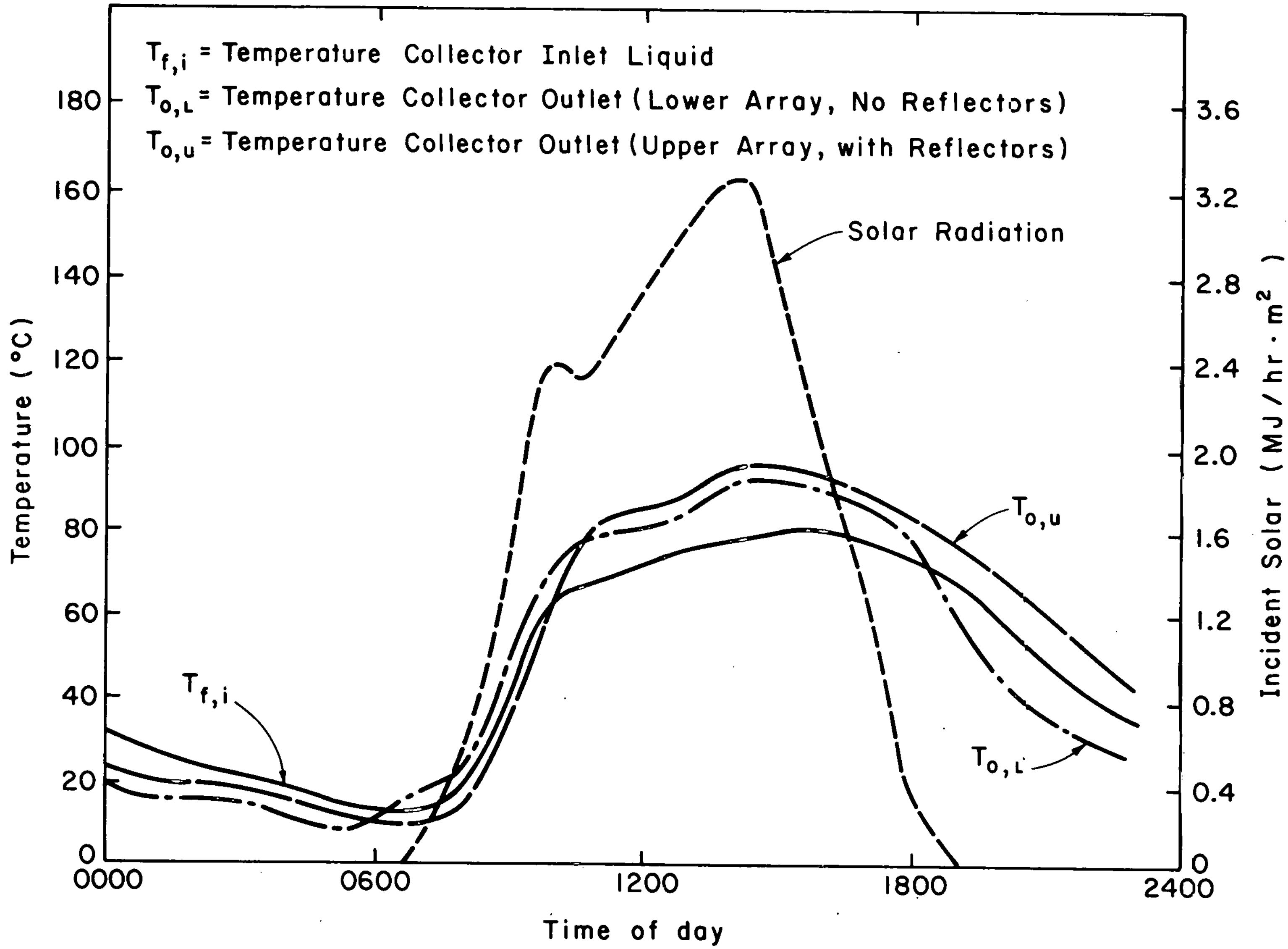


Figure 4

3/16/77

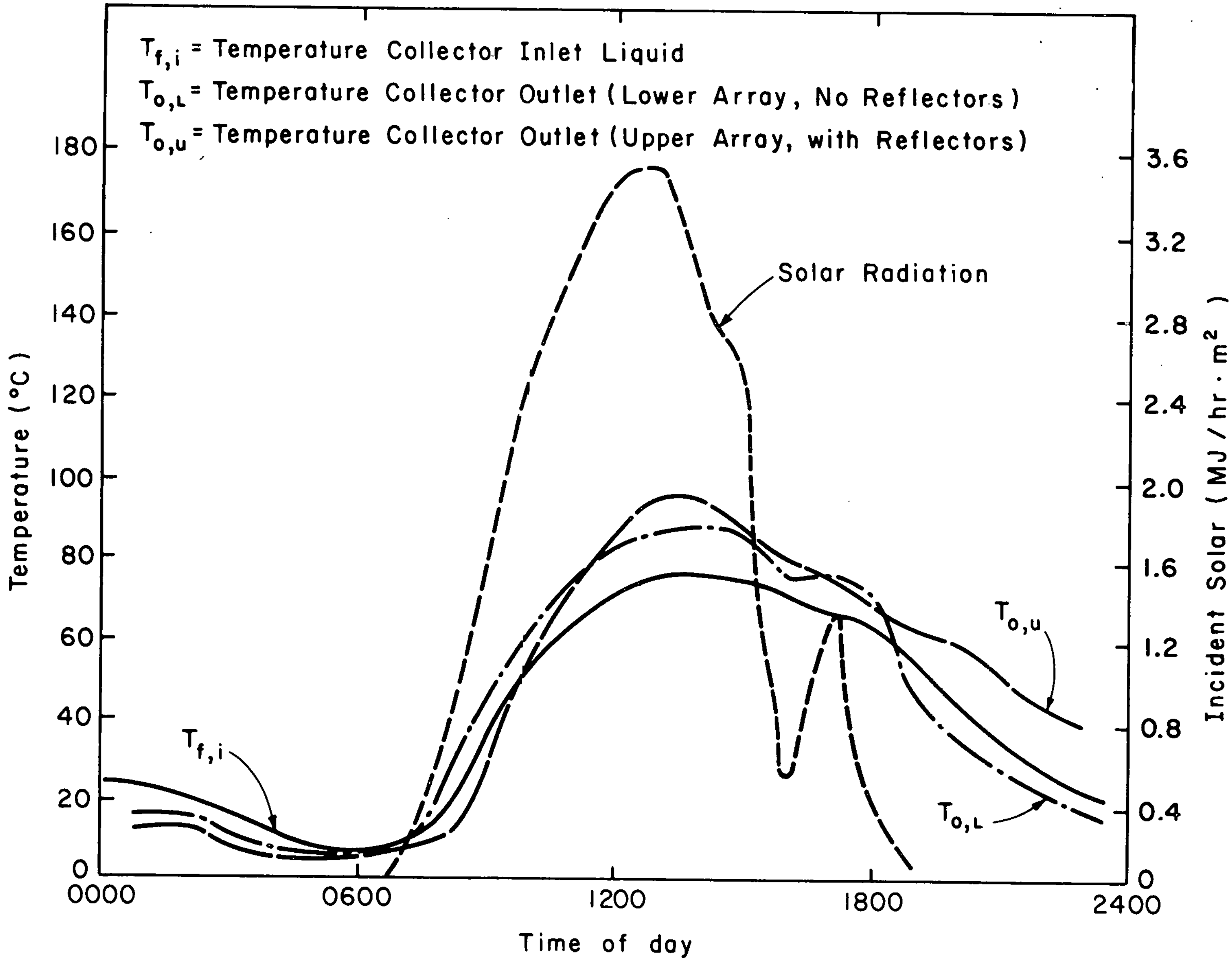
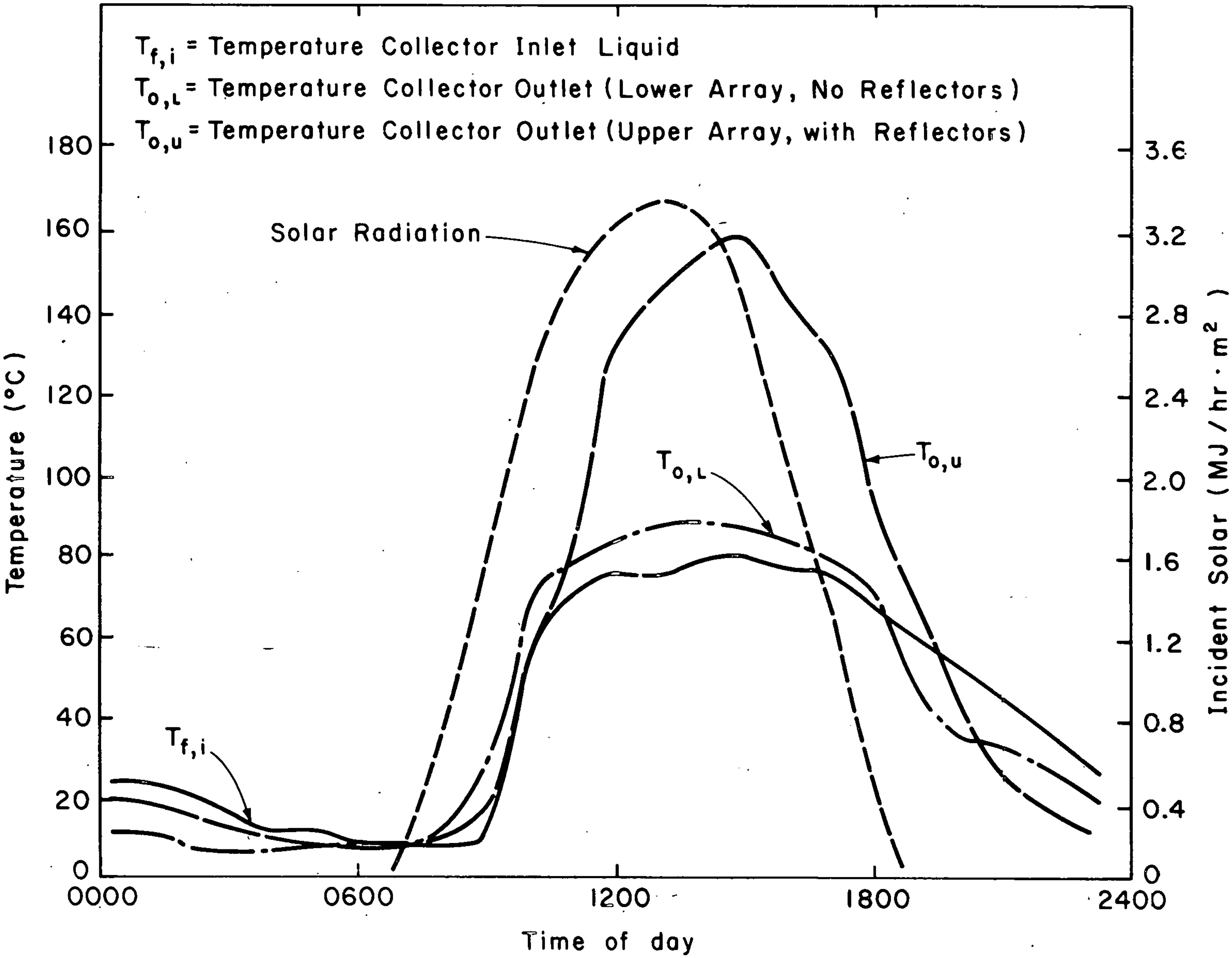


Figure 5

3/19/77



3/22/77

Figure 6

(beam and diffuse) threshold of about 41 Btu/hr·ft^2. Experimental data at CSU Solar House III indicates the threshold is slightly higher at 50 Btu/(hr)(ft^2).

Stagnation Temperature

The highest stagnation temperature recorded to date was 280°C (540°F) at a solar intensity of 769 w/m^2 (272 Btu/hr·ft^2).

REFERENCES

1. (COO-2867-1) Toxicological Evaluation of Liquids Proposed for Use in Direct Contact Liquid-Liquid Heat Exchangers for Solar Heated and Cooled Buildings, by Roy M. Buchan, Joe R. Majestic, and Robin Billau, Topical Report Prepared for the U.S. Energy Research and Development Administration, September 1976. Solar Energy Applications Laboratory, Colorado State University, Fort Collins, Colorado 80523, John C. Ward, Principal Investigator.

2. Owens-Illinois,(D.C. Beekley), Private Communication.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1977-740-094/236