

CONF-760842-3
NASA TM X-73519

**NASA TECHNICAL
MEMORANDUM**

NASA TM X-73519

**INITIAL OPERATION OF A SOLAR HEATING AND COOLING
SYSTEM IN A FULL-SCALE SOLAR BUILDING
TEST FACILITY**

by Richard H. Knoll, David Miao, Irvin L. Hamlet,
and Ronald N. Jensen
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER presented at the
International Solar Energy Society Conference
Winnipeg, Canada, August 15-20, 1976

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

INITIAL OPERATION OF A SOLAR HEATING AND COOLING SYSTEM

IN A FULL-SCALE SOLAR BUILDING TEST FACILITY

Richard H. Knoll*, David Miao*, Irvin L. Hamlet†, and Ronald N. Jensen†

*NASA-Lewis Research Center
†NASA-Langley Research Center

ABSTRACT

The Solar Building Test Facility (SBTF) located at Hampton, Virginia became operational in early summer of 1976. This facility is a joint effort by NASA-Lewis and NASA-Langley to advance the technology for heating and cooling of office buildings with solar energy. Its purposes are to (1) test system components which include high-performing collectors, (2) test performance of complete solar heating and cooling system, (3) investigate component interactions and (4) investigate durability, maintenance and reliability of components.

The SBTF consists of a 50,000 square foot office building modified to accept solar heated water for operation of an absorption air conditioner and for the baseboard heating system. A 12,666 square foot solar collector field with a 30,000 gallon storage tank provides the solar heated water. A description of the system and the collectors selected is given here, along with the objectives, test approach, expected system performance and some preliminary results.

INTRODUCTION

The Energy Research and Development Administration (ERDA) and the National Aeronautics and Space Administration's Lewis Research Center are jointly conducting research and technology (R&T) on solar cooling of buildings. A part of this Lewis effort involves solar heating and cooling research to be carried out jointly by Lewis and Langley in a Solar Building Test Facility (SBTF) at the Langley Research Center in Hampton, Virginia. This project began in 1973 when personnel from the Lewis Research Center proposed using solar energy in conjunction with a new office building planned for construction at the Langley Research Center (ref. 1). Lewis was to be responsible for selection of collectors as well as the overall system concept and have prime responsibility for the overall research program including data reduction and interpretation. Langley was to carry out detailed design and construction, and be responsible for the operation of the system as well as to participate in defining the research program and in data interpretation.

The SBTF project provides an experimental test bed to (1) test system components which include high performance collectors, (2) test performance of complete solar heating and cooling systems and investigate component

STAR category 44

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED July

E-8931

interactions, and (3) investigate durability, maintenance and reliability of components. In addition the solar system is designed to provide a major portion of the buildings heating and cooling energy requirements.

SBTF basically consists of a 50,000 square foot single story office building that has been modified to accept solar heated water for operating its absorption air conditioner and baseboard heating system. A 12,666 square foot solar collector field utilizing seven different collector designs provides the heated water, and a 30,000 gallon tank is used for storage. SBTF has just come "on-line", and it is the purpose of this paper to describe the facility, its capabilities, and the general test plan to be used. Additionally, the rationale for the types of solar collectors selected as well as some preliminary system predictions and experimental results are given.

DESCRIPTION OF SYSTEM

The Solar Building Test Facility (SBTF), shown in figure 1, consists of an office building modified to accept heat from an adjoining solar collector field to both heat and cool the building. The solar system was designed to facilitate research on solar heating and cooling subsystems, as well as to provide a significant portion of the buildings heating and cooling requirements.

Building Details. - The office building is a 50,000 square foot single story structure designed to house over 300 people. The building has been designed to conserve energy through the use of extra insulation, tinted and recessed windows, flowing exhaust air through the light fixtures, using outside air for air conditioning when the ambient air temperature is appropriate, and allowing greater temperature excursions within the building during non-working hours. The building's environmental system includes both an air-cooling system and perimeter baseboard heating. The chilled water for air cooling is provided by a standard 170-ton lithium-bromide absorption chiller. Hot water for operation of the absorption chiller as well as the baseboard heating is provided by solar energy backed up by a conventional fossil-fired, steam-to-hot water supply. The steam-to-hot water converter (heat exchanger) can fulfill 100 percent of the building's energy requirements if needed.

The equipment for the building's heating, ventilating and air conditioning (HVAC) system is located in a 3000-square-foot second-story structure ("penthouse") near the center of the building. Also housed here is the control center and data-handling system for the solar heating and cooling system.

Flow System Details. - Details of the flow system utilized for the solar heating and cooling system are shown schematically in figure 2. Major subsystems are: (1) the solar collector field of which one of the 12 rows is shown; (2) the 30,000 gallon hot water (H.W.) storage tank; (3) the steam-to-hot water converter (conv.) used as the auxiliary heat source; (4) the baseboard heating system and (5) the absorption chiller

(Trane Model CLH) with its cooling tower (C/T) and chilled water loop. Also depicted is an additional 30,000 gallon storage tank that could be used for chilled water storage if deemed desirable. The actual use of the additional storage tank, whether for chilled water or perhaps another hot water storage system at some other temperature, will be determined at a later date when some operational experience on the existing system is gained. This experience in conjunction with the results from the analytical modeling of the system will be used to help determine a desirable storage temperature.

Other elements shown in figure 2 are: the various pumps and their design flow rates; some of the key flow control valves and the unit heaters (U.H.) used in various equipment areas of the building.

The flow system has been designed to allow several different control modes with little or no change in the existing plumbing. The design control mode for initial system operation consists of four steps as follows: (1) balance step where the building HVAC system energy requirements are met by the solar output and there is direct flow between the solar collector field and the absorption chiller or baseboard heating; (2) excess solar energy step where a portion or all of the hot water from the collector field is directed to the hot water storage; (3) storage usage step where little or no energy is available from the collector field and hot water is withdrawn from the top of the HW storage tank for supplying the building energy requirements; and (4) supplemental heating step where hot water is withdrawn from the steam converter to supplement or replace the flow from the field or storage.

Some additional characteristics of the flow system are as follows:

1. Chromate treated water is used for corrosion protection (about 800 ppm).
2. Single loop system to gain 5-15° F normally lost in heat exchanger between field and storage tank.
3. Freeze protection of collector field provided by flowing warm water from storage or from auxiliary heat source. System drainage for freeze protection is also possible in an emergency situation. Glycol was not used due to cost and heat exchange efficiency.
4. Storage tanks are surplus vacuum-jacketed liquid nitrogen tanks and may not be representative of cost-effective storage tanks for solar systems.
5. Steel pipe was used to keep first costs down.
6. Temperature operated control valves have been installed in such a manner that computerized control of the valves can be utilized at a later date if deemed desirable from a research standpoint.

Solar Collector Field. - The solar collector field (see fig. 1) is located on a plot of land adjacent to the office building and at ground level, rather than on the building roof; this location was selected to facilitate access to the experimental field for changing and/or servicing collectors. The collectors face due south and are tilted 32° to the local horizontal. The particular tilt selected roughly optimizes the total energy collected for the year. The lower angles were favored due to the relatively high air conditioning requirements.

Figure 3 is a schematic depicting the general field layout and flow control zones. There are 12 rows of collectors each capable of handling 51 three by eight foot collectors totaling about 600 collectors or up to about 14,700 square feet of collector area for the entire field. Each row, with the exception of rows 1 and 2, has its own temperature controlled valve and flow meter to both control and measure the flow through the individual rows. Rows 1 and 2 have provisions for feeding 3 and 2 separate flow control zones, respectively. A future plumbing modification will enable independent control and flow through each of these five subsections giving a total of 15 separate flow control zones for the field. This would allow simultaneous testing of up to 15 different types of collectors. Provisions for the smaller zones in rows 1 and 2 were primarily made to keep overall expenditures down for potentially high cost collectors.

The collector rows are connected in parallel between the two main headers. The main inlet header servicing each individual row is buried (dotted line on fig. 3) to allow vehicle passage between the rows from the east end of the field. All lines both above and below ground are insulated. There is an eight foot wide access area between adjacent rows. The main outlet header on the west end of the field is located above ground. Figure 4 is another schematic giving further detail for a typical collector row. The main inlet and outlet headers servicing the individual rows are 4 inch schedule 40 carbon steel pipe. The inlet and outlet row headers between which the 51 collectors are connected in parallel are $1\frac{1}{2}$ inch schedule 40 carbon steel pipe. Steel braid reinforced rubber hoses run between the headers and the individual collectors. Bypasses are provided around the temperature control valves to insure that a minimum flow will always be maintained through the collectors. Each row can be valved out of the system if necessary. Air vents and relief valves set at 75 psig are also included in each row. Collector working pressure is 65 psig. All collectors for the field had to be hydrostatically tested at 100 psig with no leakage before acceptance.

Instrumentation. - Instrumentation of the solar heating and cooling system can be grouped into three general categories: (1) weather and insolation instrumentation, (2) collector field instrumentation, and (3) flow system instrumentation. In the first category data are taken on wind speed and direction, ambient temperature, humidity, total and diffuse insolation in the horizontal plane and total insolation in the plane of the collectors.

Typical collector field instrumentation, shown in figure 5, consists of platinum resistance temperature sensors on the inlet header, outlet header and mid-outlet header of each row. Row flows and pressure drops across the entire row are also recorded. Not shown are thermocouples attached to the absorber plate of each collector. A representative sample of these thermocouple readings are recorded to help determine any long term degradation of the collectors.

Flow system instrumentation consists of platinum resistance temperature sensors, pressure and pressure drop sensors and flow meters located in strategic spots throughout the flow system. Figure 6 depicts the locations of the pressure and flow measurements. Not shown are the temperature measurements, however, they are located at each major flow junction

and on the inlet and outlets of the collector field, storage tanks, hot water side of absorption chiller, chilled water side of absorption chiller, cooling tower and baseboard heating system.

The instrumentation for the entire solar heating and cooling system basically is designed to provide information on how much energy falls on the collector field, how much is collected by the system, how much is effectively utilized to satisfy the building energy requirements and how much does the building require for the given weather conditions.

Data Handling System. - The data handling system utilizes a Xerox 514 minicomputer both for processing the data and for providing future computerized control of various system functions. On line data processing includes converting the raw data into engineering units as well as performing several key calculations to monitor the collector performance, solar system performance, and to account for energy usage or storage throughout the system. All data (176 channels) are recorded on magnetic tape for final processing at the Lewis Research Center. Data are taken continuously for alarm purposes, but are only recorded at five minute time intervals. Each data point either for record or display is averaged over a 10 second time interval.

The data handling system also includes a cathode ray tube (CRT) for data display and a line printer for hard copies of the CRT images. CRT images of all recorded data are available as well as images displaying calculated values of instantaneous, hourly and daily performance of the various collectors and the system (efficiency, heat transfer rates, energy used or stored and building energy requirements). Hard copies of daily performance summaries are automatically taken each day.

GENERAL TEST APPROACH

The instrumentation and software for the project are designed to (1) automatically provide comparative test performance of the various collectors under actual field conditions and (2) record the effectiveness for utilizing the solar energy collected for various flow control modes. Initial efforts will involve determining the performance of the installed system with later efforts delving into system improvements. Table I lists our anticipated efforts for the first year of operation.

A considerable effort will be directed towards solar cooling, that is, determining what cost-effective improvements (if any) may be required in absorption chillers or their necessary subsystems (collectors, storage, etc.) to make solar cooling a viable alternative to current methods of cooling. An important by-product of the program will be the gathering of relatively long term data on several high performing collectors. Collector maintenance requirements, reliability and potential performance degradation will be monitored throughout the anticipated five year program. New or improved collector designs will be periodically added to the field. When this occurs representative samples of the collectors being replaced will be retained in a designated area of the field in order to continue reliability, maintenance and degradation studies on that particular solar collector design.

Accompanying the experimental program is an analytic effort. A Lewis modified and expanded version of the University of Wisconsin code TRNSYS has been used to model the solar heating and cooling system. The program is currently being used to predict system performance in the various operating modes using 1962 hourly weather data (a representative year) and building load profiles generated with the NECAP program (ref. 2). Inputs to and results from the analytic model will be compared with actual data to: (1) establish the applicability of the input data, (2) validate the system simulation and (3) identify areas where component modeling improvements are in order. The resulting validated simulation program will then be used to give future physical or operating changes to the system.

COLLECTOR SELECTION

The first full set of solar collectors for SBTf was obtained through a competitive, fixed-price procurement using the criteria summarized in Table II. In general, certain mechanical and fluid interfaces had to be met in order to be compatible with the given application. A minimum thermal performance specification was also imposed to limit the selection to the higher performing collectors required for absorption air conditioning systems.

All collectors that met the required specifications were then compared on the basis of the cost per unit rate of energy output. Other factors that influenced how many collector designs were selected are also listed in the table. The collectors selected on this basis are listed in table III along with some details of their construction. Six different absorber plate coatings, three different glazing arrangements and two different absorber plate materials are represented. The primary difference between the last two collectors in the table is that the Martin collector utilizes a wood frame whereas the Libbey Owens Ford collector utilizes an aluminum frame. Total usable collector area in the field is 12,666 square feet.

Baseline tests on each collector type selected were performed at the Lewis Research Center in an indoor simulator (ref. 3) to: (1) determine the performance of the collectors prior to prolonged field use, (2) ensure that the minimum thermal efficiency specification is met and (3) determine if prolonged operation without coolant causes any degradation in collector performance. These tests are now nearing completion and will be reported at a later date. The efficiency curves (as per ref. 3) generated in these baseline tests are also used in conjunction with the analytical model to determine if overall system performance can be predicted.

EXPECTED SYSTEM PERFORMANCE

A preliminary estimate of system performance for a representative weather year (1962) and a given set of solar system input parameters is given in figure 7. The building load (QL) calculations were provided by

the Langley Research Center and are from NASA's ENERGY COST PROGRAM (NECAP) as described in reference 2. The energy provided by the solar system (Q_L - the auxiliary heat required, Q_{aux}) was calculated using a Lewis Research Center modified versions of TRNSYS as described earlier. These are the first detailed attempts at determining how much energy the solar system can provide and are not necessarily optimum from an energy utilization standpoint. The results, however, do demonstrate the magnitude of energies involved.

The building energy requirements are dominated by the air conditioning requirements as evidenced from figure 7. Total building energy needs for the representative weather year selected are about 1500×10^6 Btu. For the solar system case shown, the collector valves were set to deliver relatively high temperature water only, that is, the collector row valves were set to begin opening at 180° F in the winter months and 190° F during the summer months.

With this setting the solar system provided 75 percent of the total yearly needs of the building. Higher percentages of the total requirements provided by solar could be achieved, for example, by trading off collector performance with absorption machine performance and by adjusting the various valves and storage tank temperatures. Future analytical efforts will concentrate on (1) system performance optimization, (2) sensitivity studies, and (3) cost-effectiveness studies.

PRELIMINARY OPERATIONAL RESULTS

The facility is currently undergoing shakedown tests. It should be fully operational by the third quarter of this year. However, some early experience has already been gained in facility operation. Some of these highlights are:

(1) The system has operated on direct solar or stored solar energy for 25 of the first 42 days of operation (since mid June 1976).

(2) Typical operation has consisted of operating the absorption chiller on hot water from the steam-to-hot water converter until roughly 11:00 A.M., when the switchover to solar is made.

(3) Adequate cooling for many days has been achieved using 185° F water from the steam-to-hot water converter and/or the solar system for operation of the absorption chiller, rather than the design operating temperature of 230° F.

A plot of one days performance is given in figure 8 for July 13, 1976, where insolation normal to the local horizontal and collector inlet and outlet temperatures are shown as a function of time. Prior to 11:00 A.M. the hot water for the absorption chiller was provided by the steam converter. Just after 11:00 A.M. a switchover to solar was made and continued until 4:45 when the system was switched back to the converter again. The average ambient temperature was 77° F. The building's interval environment was maintained at a temperature of 76° and a relative humidity of 56 percent throughout the day. It should be noted that only $3/4$ of the available collectors (9 out of 12 rows) were operating

this particular day. Despite this, reasonable collector outlet temperatures were achieved and the solar system was capable of effectively handling the cooling requirements of the building (which consisted primarily of lighting and people heat loads).

During initial operations we have encountered our share of startup problems, in both nonsolar and solar categories. Leaky fittings and failure of turbine flow meters due to debris in the water characterize some of the nonsolar problems. Some of the solar-related problems were: (1) some collectors were damaged during shipment from manufacturers, (2) glass breakage (on one collector) after field installation-cause unknown, (3) delays in bringing on-line collectors with aluminum absorber plates (25% of field) because of some difficulty in locating suitable nonmetallic connectors, (4) some (<10) collectors leaked due to damage by a plumbing contractor and/or a vulnerable inlet and outlet design not yet fully determined, and (5) clouding of some collector glazings due to outgassing of foam insulation at temperatures near 250° F. Most of these problems are solvable of course. They are noted here to illustrate the variety of problems that can be encountered in bringing a solar heating and cooling system on-line.

CONCLUDING REMARKS

A major solar heating and cooling test facility, SBTF, is now on-line. Its overall purpose is to help advance the technology for practical cost-competitive solar heating and cooling systems that utilize absorptive air conditioners and liquid-cooled collectors. The flexibility in the design approach used for the SBTF will allow: (1) investigation of several energy utilization strategies, (2) investigation of problems resulting from component interactions, system dynamics and the transient nature of real weather and building loads, (3) experimental studies on multiple storage temperatures and (4) easy addition to or replacement of existing collectors with new advanced designs. Moreover, the data handling system, with its dedicated minicomputer, has been designed and sized in such a manner that it too can be readily expanded to provide system control or to accommodate additional research data.

The test program will focus on solar cooling systems (absorptive air conditioning), and the maintenance, performance and reliability of high performing collectors under field conditions. It is planned to modify or add new solar subsystems throughout the test program. The choice of subsystems modification or addition will be guided by both experimental results and results from analytically modeling the proposed changes. New research and technology advances that evolve from other ERDA-sponsored research will also be integrated into future SBTF activities.

REFERENCES

1. R. G. Ragsdale and D. Namkoong, The NASA Langley Building Solar Project and the Supporting Lewis Solar Technology Program. NASA TM X-71600 (1974).
2. R. H. Henninger (Ed.), NECAP - NASA's Energy-Cost Analysis Program, Part I - User's Manual. NASA CR-2590, Part I (1975).
R. H. Henninger (Ed.), NECAP - NASA's Energy-Cost Analysis Program, Part II - Engineering Manual. NASA CR-2590, Part II (1975).
3. F. F. Simon, Flat-Plate Solar-Collector Performance Evaluation with a Solar Simulator as a Basis for Collector Selection and Performance Prediction. NASA TM X-71793 (1975).

TABLE I. - LISTING OF ANTICIPATED TEST SERIES FOR FIRST YEAR

Test series I	Shakedown and startup tests for solar collector field and HVAC system
Test series II	Field performance, comparative collector tests and initial energy utilization studies for solar air conditioning during summer-fall operation
Test series III	Field performance, comparative collector tests and energy utilization studies for winter operation
Test series IV	Energy utilization studies comparing chilled water or additional hot water storage temperatures
Test series V	Investigation of operation envelope of absorption machine and optimization of combined collector-absorption machine performance

TABLE II. - COLLECTOR CRITERIA FOR SBTf

Specifications:

Minimum thermal performance
 Meet mechanical and fluid interfaces
 30 lb/ft² wind and 20 lb/ft² snow loads
 Hydrostatic test at 100 psig
 Complete drain at 32° tilt (freeze protection)
 Housing vent to avoid any pressure build-up
 Capable of dry operation or specify limits

Selection:

After meeting specs collectors were compared on basis of:

$$\frac{\text{Minimum cost} \left(\frac{\$}{\text{Btu/hr}} \right)}{\text{Energy output}} \text{ at } \begin{cases} T_{\text{inlet}} - T_{\text{amb}} = 110^{\circ} \text{ R} \\ \text{INSOLATION} = 220 \frac{\text{Btu}}{\text{hr ft}^2} \end{cases}$$

Final purchase influenced by:

200 K dollar limit
 Fill the field
 Desire to maximize energy output of field
 Desire to have several basically different designs
 (glazing, coating, absorber plates and construction)

TABLE III. - INITIAL COLLECTOR MIX FOR SBTf

Collector details			No. rows (area)	Manufacturer
Glazing	Coating	Absorber plate		
1 glass	Black chrome	Steel	2 (2228 ft ²)	Chamberlain
2 glass	Black chrome	Steel	3 (3342 ft ²)	Chamberlain
2 glass	Sel. paint	Steel	3 (3342 ft ²)	Chamberlain
1 glass	Black nickel	Steel	1 (714 ft ²)	Sun source
2 lexan	Alcoa Sel.	Aluminum	1 (1177 ft ²)	General Electric
2 glass	Black paint	Aluminum	1 (822 ft ²)	L.O.F.
2 glass	Black anodized	Aluminum	1 (1042 ft ²)	Martin

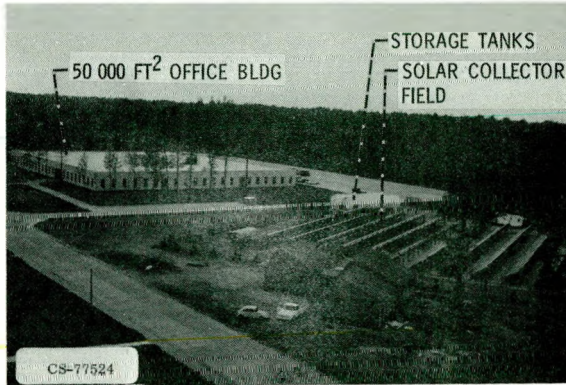


Figure 1. - The Solar Building Test Facility.

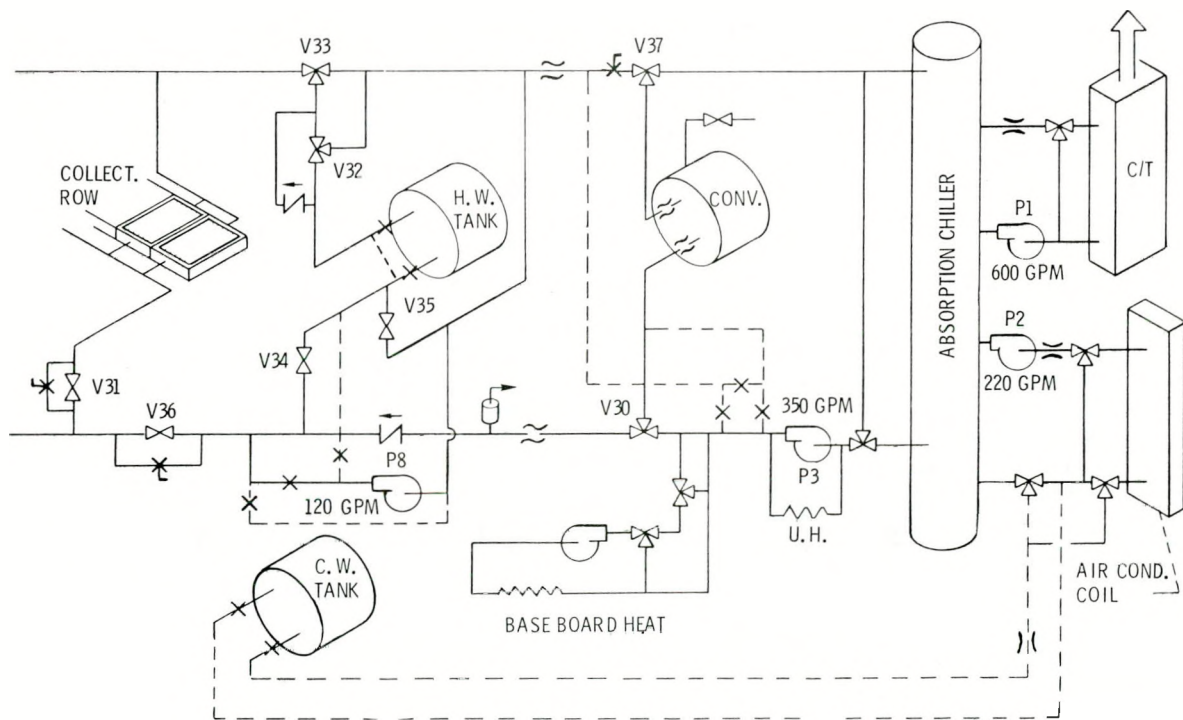


Figure 2. - Flow schematic for SBTF.

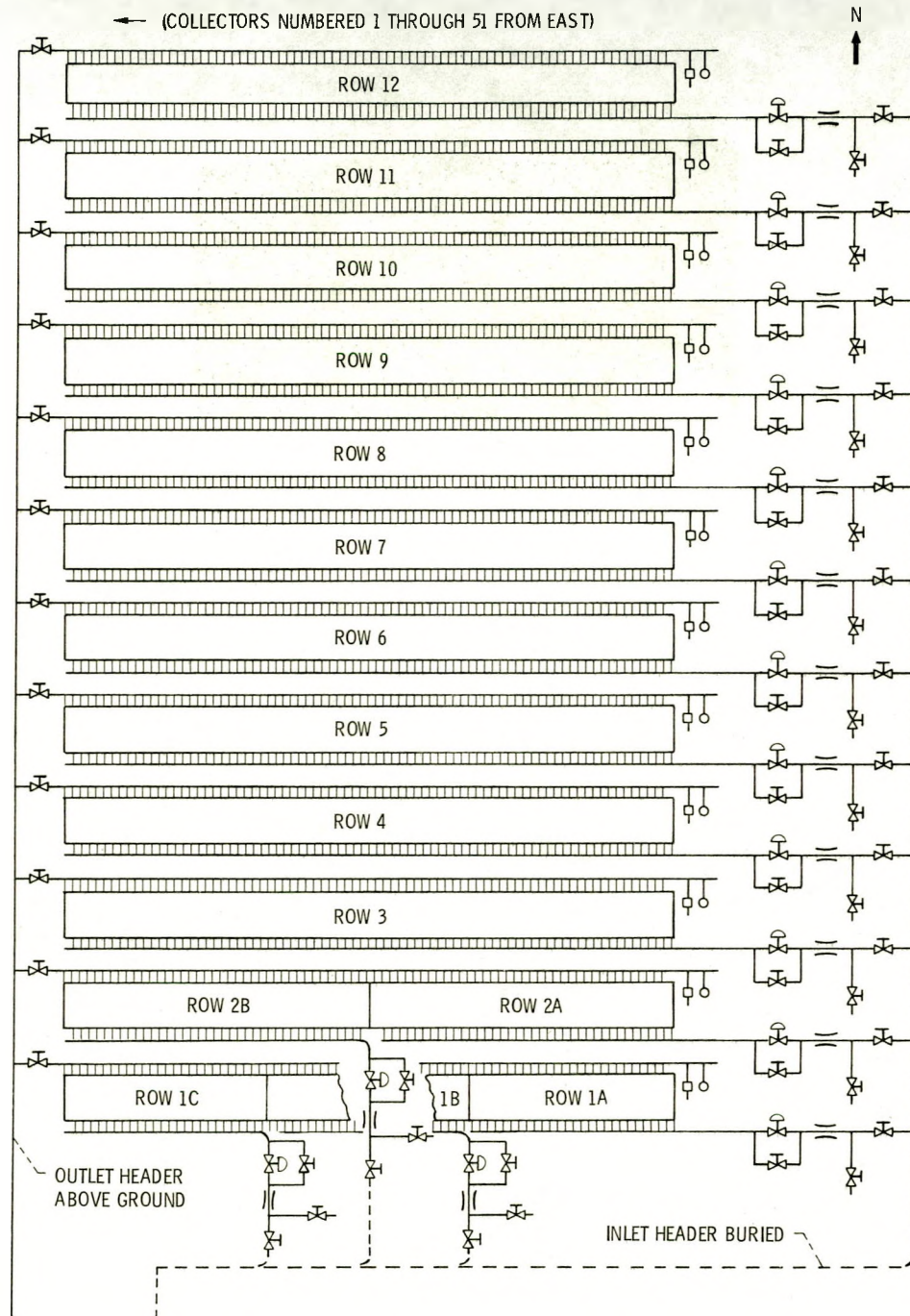


Figure 3. - General layout of solar collector field.

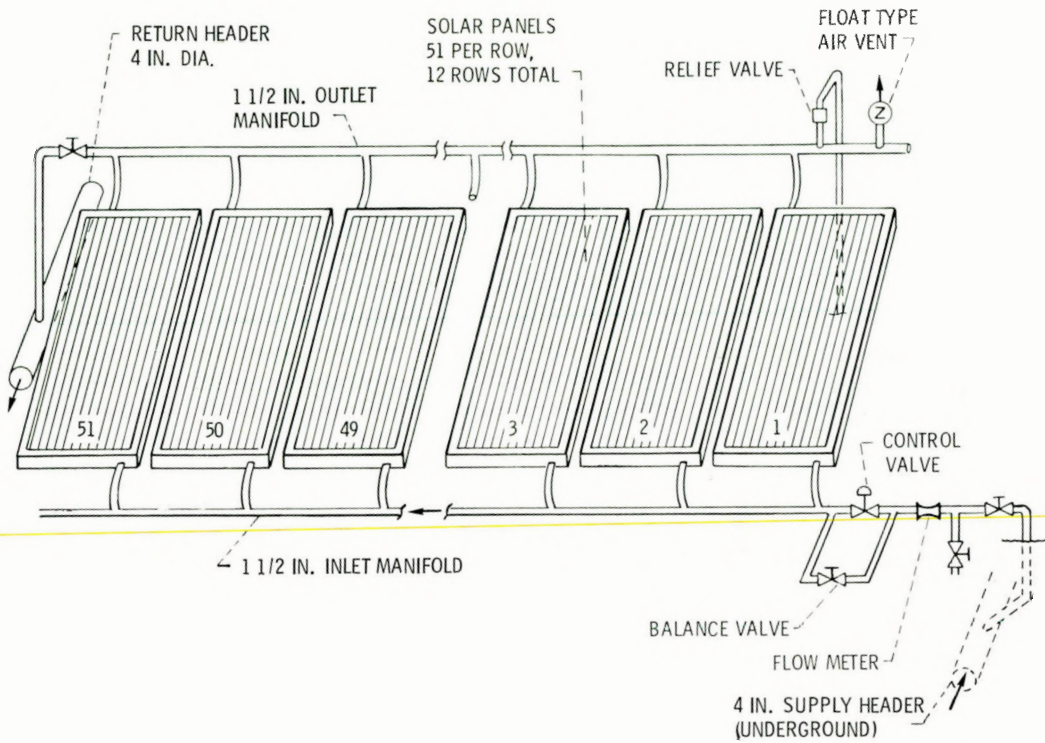


Figure 4. - Flow schematic for a typical collector row.

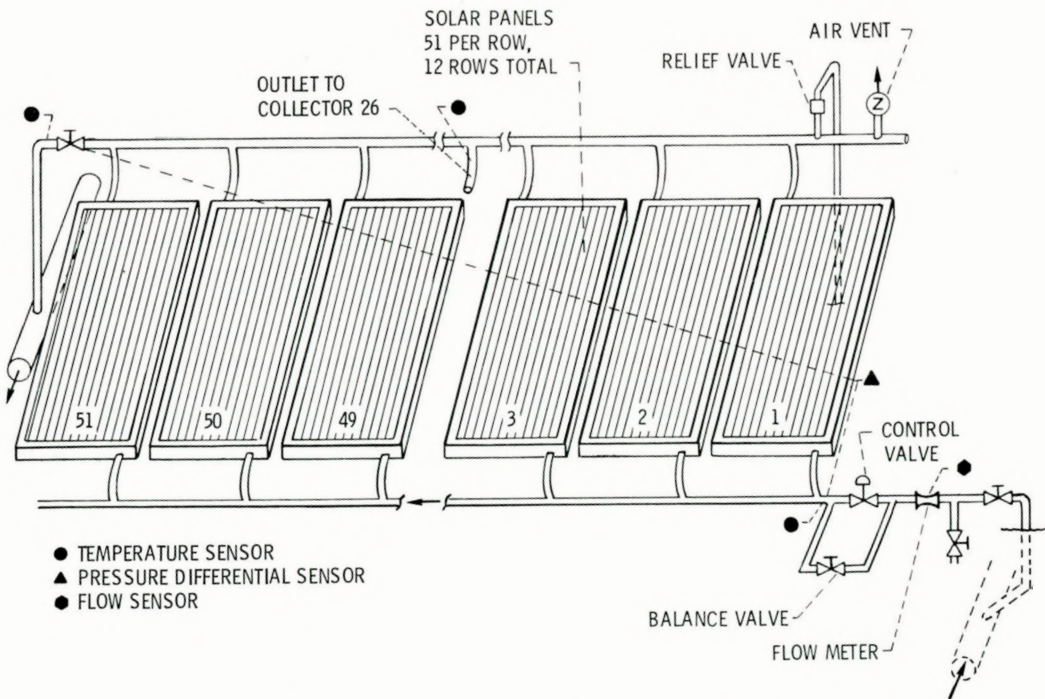


Figure 5. - Instrumentation for collector row 4 (typical for all rows).

E-8931

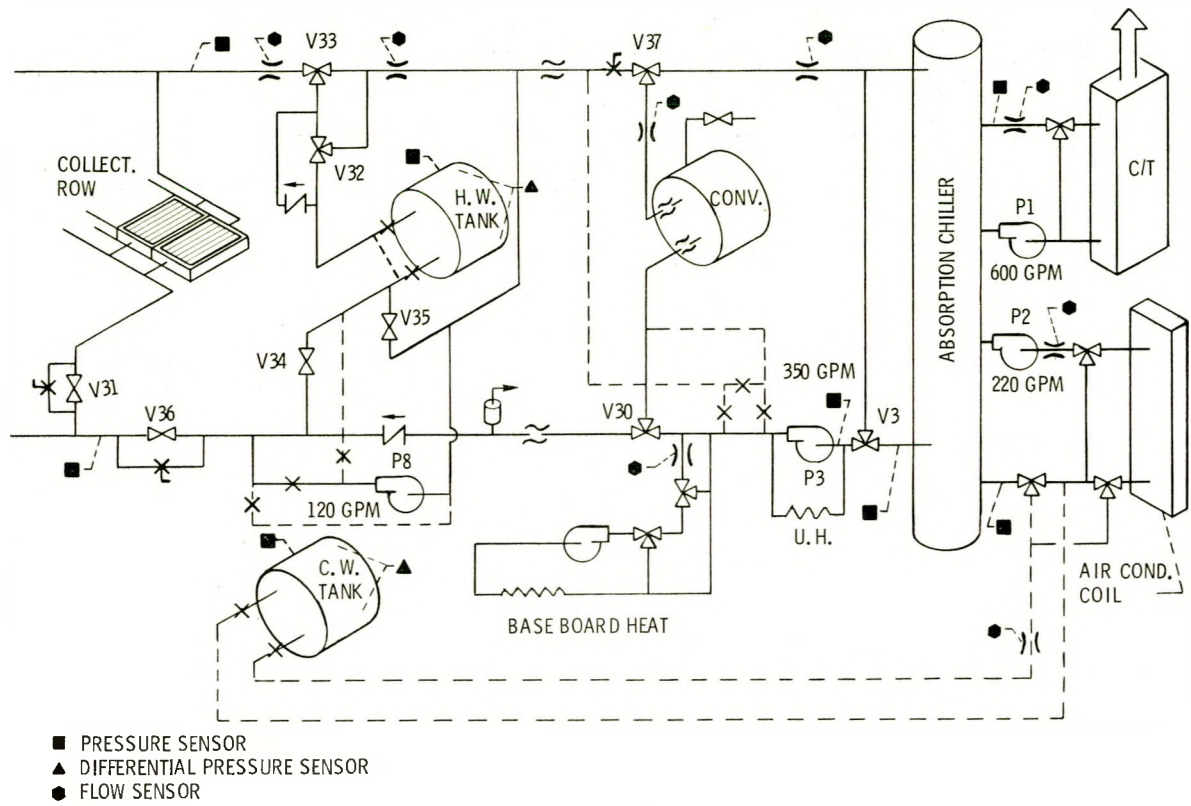


Figure 6. - Location of solar system pressure sensors and flow meters.

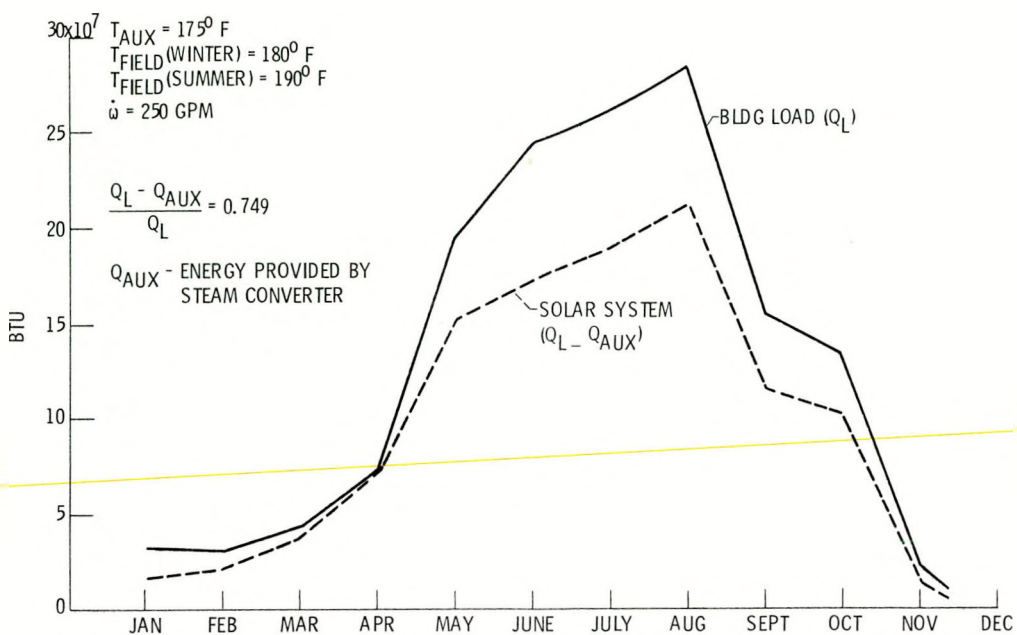


Figure 7. - Typical yearly performance for a representative set of valve operating temperatures.

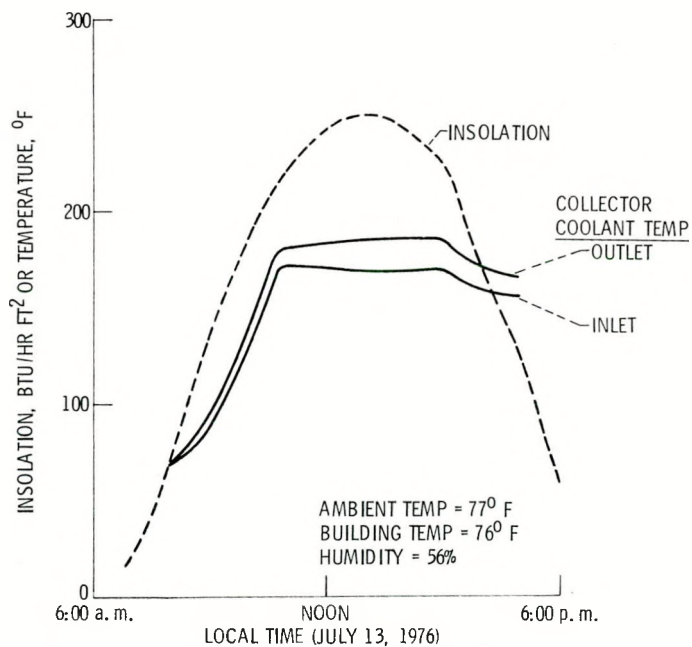


Figure 8. - Experimentally measured insolation and solar collector field inlet and outlet temperatures for a typical clear day.