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SANTA CLARA, CALIFORNIA, COMMUNITY CENTER COMMERCIAL SOLAR DEMONSTRATION PROGRESS REPORT—SIX MONTHS DATA ACQUISITION AND ANALYSIS OF COOLING PERFORMANCE

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March 1978

Work Performed Under Contract No. EY-76-C-03-1083

Mechanical Engineering Department
The University of Santa Clara
Santa Clara, California

U.S. Department of Energy

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COMMERCIAL SOLAR DEMONSTRATION
PROGRESS REPORT-SIX MONTHS DATA
ACQUISITION AND ANALYSIS OF COOLING PERFORMANCE

CONTRACT NO. EY-76-C-03-1083

prepared by
W. NIEMEYER, S. AYRAUD, M. HEMSCH, F. BROWN

MARCH 1978

MECHANICAL ENGINEERING DEPARTMENT
THE UNIVERSITY OF SANTA CLARA
SANTA CLARA, CALIFORNIA 95053

for

CITY OF SANTA CLARA
1500 WARBURTON AVENUE
SANTA CLARA, CALIFORNIA 95050

and the

UNITED STATES DEPARTMENT OF ENERGY
DIVISION OF CONSERVATION AND SOLAR APPLICATIONS

ABSTRACT

The Santa Clara Community Center is a 27,000 sq. ft. one-story building set in a mediterranean climate. The peak summer cooling load is estimated to be 5.9 x 10^6 Btu/day and is roughly twice the peak winter heating load. The solar-driven hydronic system includes 7,085 sq. ft. of double-glazed flat plate collectors with a selective coating, two 25-ton ARKLA absorption chillers, a 50,000 gallon stratified cold storage tank and a 10,000 gallon hot storage tank. The solar system is designed to satisfy roughly 80% of the annual thermal energy requirements. A boiler is used for backup. The system is well instrumented and has been providing operational data including detailed energy balance information since April 1977. Data for one complete cooling season has been obtained. Detailed results are presented in this report.

The data acquisition system used has "event sense" capability. Hence, the collected data include the periods of operation in each of the system modes. This capability makes it possible to calculate the auxiliary electrical and gas consumption of the present solar system and to compare it to the estimates for the original non-solar HVAC design which used vapor compression chillers. Preliminary evaluation indicates that the present system during the cooling season consumes roughly the same amount of fossil fuel energy as the original non-solar design.

ACKNOWLEDGEMENTS

It would be impossible to acknowledge all the individuals who contributed to the installation and checkout of the data acquisition system. We do wish to gratefully acknowledge the following people as representatives of their organizations: A.B. Burns, S.L. Leacock, and L.B. Anderson of Lockheed-Palo Alto; R.R. Mortensen and R. Bezerra of the City of Santa Clara; J.N. Davis of Licciardello, Davis and Associates; D. Igelmund, J. Caffey and C. Turner of Hewlett-Packard Corporation.

For their encouragement and constructive advice we also gratefully acknowledge the Project Oversight Committee: D.M. Jardine, J.I. Yellott and J.C. Ward.

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Section 1
INTRODUCTION

As part of the National Solar Heating and Cooling Demonstration Program and as part of its own program on Solar Heating and Cooling as a Public Utility, the City of Santa Clara under contract to the Department of Energy* has added a solar-powered air-conditioning, heating and domestic hot water system to its new community center building. As part of that contract, the University of Santa Clara has had personnel working on the project since June 1975.

It was recognized early in the development of the solar-driven system for the new city building that a data acquisition system (DAS) would be needed for checkout and optimization of system performance. It was also recognized that a DAS capable of real-time performance calculations would provide invaluable data on the performance of installed solar-system components. Such a DAS was selected and installed by Lockheed Palo Alto Research Laboratory and Hewlett-Packard Company. As part of this effort, the University of Santa Clara was engaged to program the DAS and provide a one-year performance analysis of the complete solar-driven system. The University also decided to continue development of the Lockheed computer model of the solar heating and cooling system for comparison with measured results (see Appendix D).

This progress report presents (1) a description of the DAS and experience to date of its operation and performance and (2) a summary and analysis of the first six months of data collection (April-September 1977). The next two sections provide an introduction to the project and a brief description of the solar heating and cooling system design.** Sections 4 and 5 describe the data acquisition system (DAS) and its operation. Section 6 discusses the operational performance of both the DAS and the solar-driven heating and cooling system.

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* Department of Energy (formerly ERDA) Contract NO. EY-76-C-03-1083

**Much of the material for these sections was obtained from references 1 and 2.

The report is concluded with a discussion of the merits of the present solar-powered system and its data acquisition system, present problems, and future work leading to the year-end contract report.

Section 2

INTRODUCTION TO SANTA CLARA COMMUNITY CENTER SOLAR HEATING AND COOLING PROJECT

2.1 DESCRIPTION OF THE CENTER

The Community Recreation Center, owned and operated by the City of Santa Clara, California, is part of the nationwide network of buildings and facilities participating in the DOE sponsored Solar Heating and Cooling Demonstation Program. The solar-driven heating and cooling system installed on this facility began full operation in the second quarter of 1977, thereby completing a project that was formulated in late 1973. A complete design report is presented in Reference 1.

The Community Recreation Center is a one-story facility with a 27,000 sq. ft. net interior area that is used by both the City government and its residents for a variety of purposes which include the following: arts and crafts classes, teenage recreation, preschool and handicapped services, and public meetings. The facility serves the community on a year-round basis, with both day and evening schedules.

The building is generally of rectangular shape with the long dimension oriented in an east-west direction, thereby making the sloping roof areas on the south side of the building ideal placement areas for the solar collectors. This building is a cooling dominated design with the peak summer cooling load (5.9×10^6 BTU/day) being approximately twice the peak winter heating load. The maxium cooling load for design-day conditions was calculated to be 65 tons.

Fixed flat-plate roof mounted collectors provide heat to underground storage via a heat exchanger. Alternatively, when the incident solar insolation permits, the heat drives one or both of two absorption chillers to produce chilled water for underground storage. Placement of major solar system components relative to the building is shown in Figure 1.

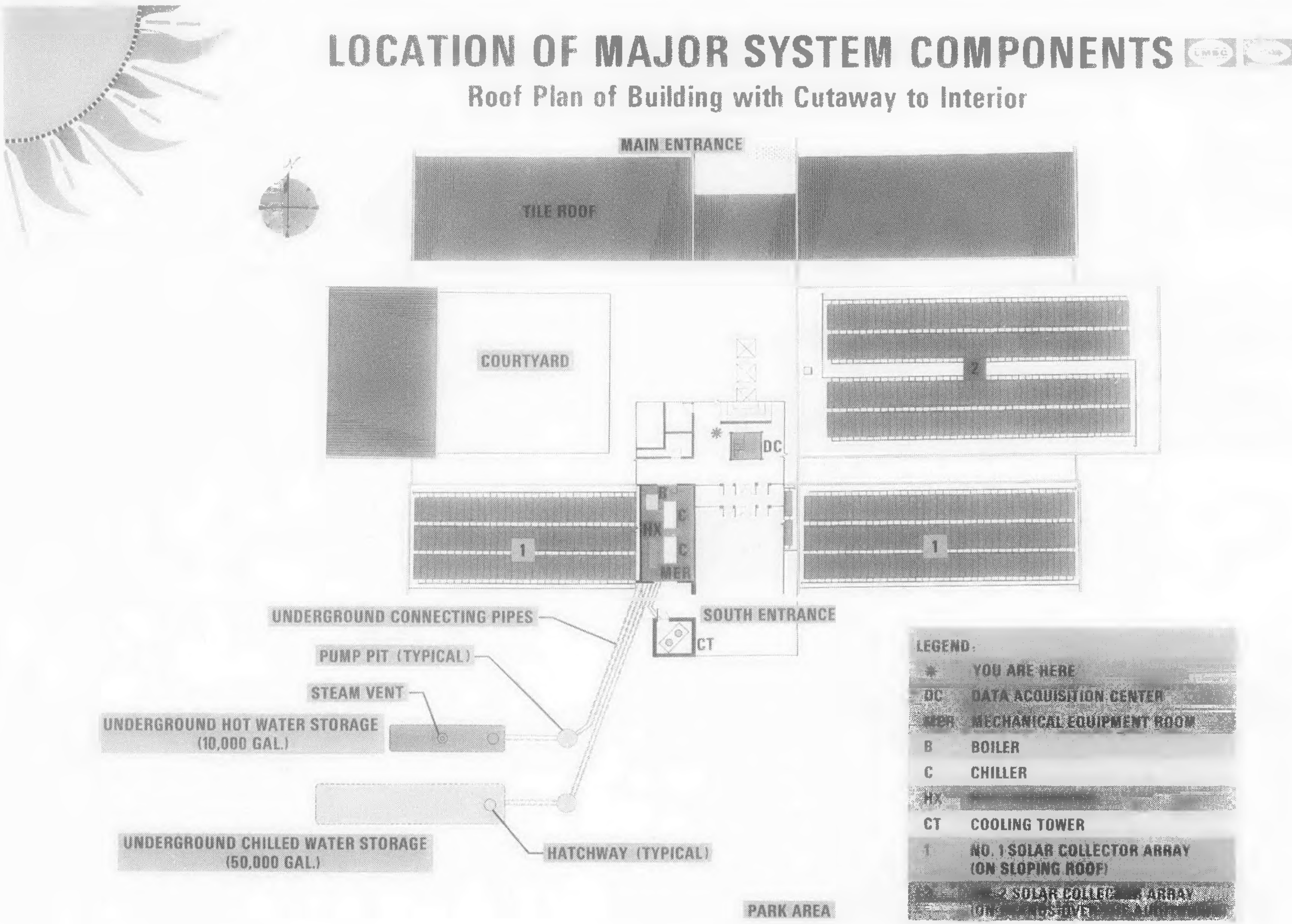


Figure 1 - Location of Major System Components

2.2 HISTORY OF THE PROJECT

In December 1973 the Santa Clara City Council approved construction of a new community recreation center to be built in the city's 52-acre central park. The Lockheed Palo Alto Research Laboratory was asked to assist the city in preparing a grant application for design and construction of a solar-driven heating and cooling system. The application was submitted to the National Science Foundation in March 1974. Ground was broken for the new building in April 1974.

In December 1974 the City received a grant entitled "Solar Heating and Cooling as a Public Utility" from NSF. Responsibility for the NSF program was transferred to the Energy Research and Development Administration when that agency was created in January 1975. Upon completing agreements with ERDA, the City authorized Lockheed to begin the conceptual design of the solar energy system. A number of contractors participated in the project. The major participants included:

David C. Thimgan, AIA	Architect
Lockheed Palo Alto Reserach Lab.	Solar Heating & Cooling System Design & Selection of Data Acquisition System
Hewlett-Packard Company	Data Acquisition System
Wilson, Jones, Morton & Lynch	Legal Consultants
G.J. Yamas & Company	Controls
AMETEK Incorporated	Solar Collectors
P.R. McCoy & Associates	Mechanical Design
Welch Construction Company	General Contractor
University of Santa Clara	Performance Evaluation
Yellott, Ward & Jardine	Oversight Committee
City of Santa Clara--Water Utility	Installation of Solar Hardware

It was apparent by January 1975 that the solar energy system would have to be retrofitted since building construction was well ahead of solar system planning. In March 1975 Lockheed identified the need for a major design change. Cost and performance predictions from computer simulations of the system originally proposed indicated that the flow control system should use constant rather than variable flow rates.

Lockheed completed the new design in June 1975. Hewlett-Packard Company volunteered to furnish much of the data acquisition system equipment on a no-charge loan basis for the 1976 calendar year. It was agreed that the City would lease the remaining HP equipment needed to complete the data system. Later in June the community center building was completed and opened for use, but without air-conditioning. Heating was provided by the gas-fired boiler.

By mid-July 1975 Lockheed had completed its outdoor testing of the first full-sized prototype models of the solar collectors supplied by Ametek. Performance met expectations and Ametek was asked to supply production models for testing. In September, Lockheed completed a detailed definition of the diffusers and piping arrangement in the cold storage reservoir. Extensive research had been performed at Lockheed to solve the problem of preserving temperature stratification in the horizontal cold tank while fluid is being withdrawn and returned to this reservoir.

By February 1976 the storage tanks had been delivered and were insulated on site before installation. After corrosion protection was applied to the inside of the tanks, the hot tank was filled for one month to cure the cement liner while work continued on the pump pits and interconnect piping between the tanks and the mechanical equipment room.

Installation of the plumbing and controls hardware had not been completed when, in mid June, the Electrician's Union went on strike. Work finally resumed on the electrical and control portion of the solar project in August. Some of the collectors had been installed before the strike and were, therefore, exposed to the summer sun in a stagnant condition. Application of white poster paint to the outer cover glass reduced internal temperature extremes.

In August, most of the remaining collectors were delivered and placed on the roof. In September, water was circulated through the completed arrays for the first time. Approximately one-fifth of the collectors developed problems, mostly excessive moisture condensation inside the boxes. The collector manufacturer completed repairs in January 1977 and insulation of the manifolding on the roof began in February.

As previously mentioned, the data system supplier (Hewlett-Packard) had generously agreed to loan several key components of the data system to the City for one year, until the end of 1976. In February 1977 the City made arrangements to purchase the data acquisition system in order to insure its future availability to the program. By mid-March, header insulation had been installed and checkout of operational modes was completed.

Section 3

SOLAR HEATING AND COOLING SYSTEM DESIGN

As owner and operator of the Community Recreation Center, the City of Santa Clara, while interested in obtaining firsthand experience with solar heating and cooling systems, was at the same time concerned that its public facility not be converted into a research laboratory. The City determined that the solar system should have minimum complexity, require minimum maintenance and, wherever possible, be fabricated from commercially available materials and components whose expected lifetime would be of the same order as that of the basic building (in excess of 30 years).

The preliminary mechanical system design, which was based on use of a fixed air volume system with individual air handlers having both a hot and cold coil, appeared to be compatible with the evolving Lockheed solar concepts. Thus, the first issues that were addressed included system interconnection and size and type of absorption chiller. An early decision was made to utilize hot-water-driven absorption chilling because no other heat-driven device was available which was capable of producing the required cooling. Consequently, one of the original concepts consisted of a collector array which provided energy to hot storage. The high temperature fluid from storage was to be pumped to the input side of a single large absorption chiller. Utilizing building load data as well as climatic/solar insolation information developed for this facility, first estimates of energy requirements on an annual basis were developed by the utilization of a modeling program developed by Lockheed.

Evaluation of this first concept showed the following undesirable characteristics:

- A single large chiller would operate off design point most of the time.
- Losses were found to be unacceptably high with the energy output from the collectors supplied to the chiller input via heat exchange with the hot storage tank.

- To fire absorption chillers at or near rated capacity required water temperatures at or above the boiling point. This would require pressurized hot storage and represent a major impact upon storage vessel cost.

At this point in the design evolution, the National Science Foundation suggested using both hot and chilled water storage. The inclusion of cold storage added a level of complexity that could not easily be accommodated in the modeling program previously utilized. By combining the results obtained from modified SIMSHAC* and TRNSYS** programs, the following limitations were discovered:

- Staging the operation of multiple chiller units was an optimum design but with the roof-area-limited collector array it was not possible to drive three of the 25 ton units available.

- Cold storage would work as planned only if stratification could be developed and maintained in the tank.

As a result of these simulations, the final configuration was selected as shown schematically in Figure 2. The system has the following significant features:

- 7,085 ft^2 collector array at 18° from horizontal
- Two absorption chillers each having a 25-ton rating
- Ambient pressure storage of both hot and chilled water
- Hot water storage: 10,000 gallons
- Cold water storage: 50,000 gallons
- Hot storage isolated from the pressurized collector loop by a heat exchanger
- Provision for the collector array to drive one or both absorption chillers directly, depending on available solar insolation
- Gas-fired auxiliary heater capable of providing hot water for direct firing of both absorption chillers independent of hot storage.

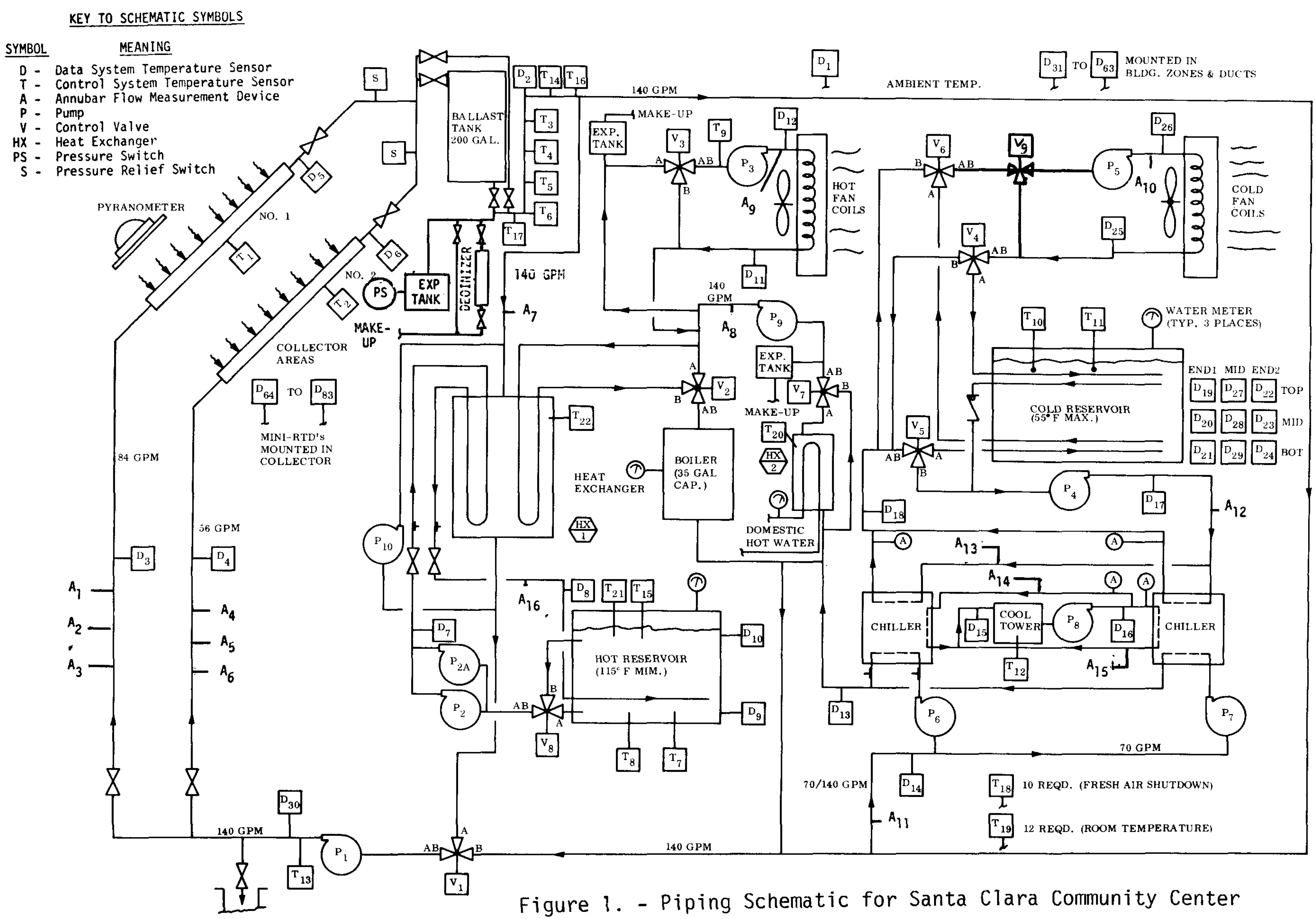


Figure 1. - Piping Schematic for Santa Clara Community Center

3.1 MAJOR COMPONENTS OF THE SYSTEM

3.1.1 Collectors

The collector used was developed by the Ametek Power System group, Hatfield, Pensylvania , to specifications prepared by the Lockheed Palo Alto Research Laboratory. The collector is a flat plate design specifically chosen to meet or exceed a noontime efficiency rating of 45 percent when the difference between the mean fluid temperature in the collector (TF) and ambient temperature (TA) is approximately 150°F and the solar flux (QI) is 300 Btu/Ft^2 hr. Efficiency is calculated on the basis of the solar flux measured normal to the surface of the collector with a collector aperature area of 16.25 Ft^2. Actual collector performance is discussed further in Section 6.

Two tempered glass plates are used in each collector box. The glass is low-iron content (0.59 percent) with 90 percent average transmission. The absorber plate is a Roll-Bond product with integral riser and header design manufactured in copper no. 122 by Olin Brass, East Alton, Illinois. The upper side of the copper absorber plate is treated with a proprietary selective coating developed by Ametek that has the following optical properties at normal operating conditions:

	Range
Absorptivity	.97 -.99 at visible wavelengths
Emissivity	.22 -.40 at infrared wavelengths

3.1.2 Absorption Chillers

The Arkla Industries, Inc. 25-ton, hot water fired, absorption cycle chillers were specified for this project, based upon their commercial availability in the capacities desired. At the flow rate of operation (70 gpm) the units operate at a derated capacity unless the firing water has a minimum temperature of 200°F. When operating at rated capacity, the coefficient of performance is rated at 0.67; thus, 445,000 Btu/hr must be supplied by the firing water to produce a cooling effect of 300,000 Btu/hr (25 tons). Firing water input can be reduced to a minimum of 222,500 Btu/hr with a proportional decrease in refrigeration capacity.

3.1.3 Storage Reservoirs

The hot water storage reservoir is a welded, cylindrical A36 steel tank, 8 ft. in diameter and 34 ft. in length. It is filled with 10,000 gallons of water. The remaining volume provides an air space at the top of the tank for the collection of steam. The exterior surface of the tank is insulated with 3.5 in. of Owens-Corning Urethane Spray System No. 304. A waterproof barrier was applied to seal the external surface of the foam against moisture. The 3.5 in. thickness of urethane foam insulation results in an R factor of 25 when the average thermal conductivity of the material is taken to be 0.14 Btu-in/hr ft^2°F.

The cold water storage reservoir is also a welded, cylindrical A36 steel tank which is 12 ft. in diameter and 52 ft. in length. The capacity of the tank is 50,000 gallons. Stratification of the fluid in the cold water storage reservoir is necessary for successful operation of the system[1]. This is accomplished with a diffusion system designed by Lockheed which employs pipes extending the length of the tank which are surrounded by baffles and use a discharge orifice pattern incorporating side-thrusting jets. The exterior surface of the cold water storage reservoir is insulated with the same urethane spray system and waterproof barrier used on the hot-water storage reservoir, except that, in this case, the thickness of the insulation is 2 inches which represents an R value of 14.

3.1.4 Piping and Insulation

The hot water piping in the system is copper. The chilled water piping is schedule 80 PVC pipe with socket weld fittings. Schedule 40 PVC piping with socket weld fittings is used in the cooling tower piping. Water in the collector fluid loop contains a 10 percent by volume concentration of propylene glycol to prevent freezing.

All piping within the fluid loops of the system is insulated with the exception of the cooling tower lines. The insulation for the collector loop is designed to keep the rate of total pipe heat loss less than approximately 3 percent of the total energy being extracted from the loop under worst case loss conditions (fluid temperature is 220°F). This translates into a loss per lineal foot of pipe of less than 18 Btu/hr.

Similarily, the hot water storage loop insulation is designed to keep the loss rate less than one-half percent for a loss per lineal foot of less than 25 Btu/hr (with a fluid to ground temperature difference of 150°F). The insulation for the chilled water loop restricts the loss rate to less than one percent for a loss per lineal foot of pipe of less than 12 Btu/hr (with a ground to fluid temperature difference of 25°F).

3.1.5 Controls

The solar-powered heating and cooling system is managed automatically by a control system consisting of relays, solid state controllers, resistance temperature devices (RTD's) and a pyranometer. The pyranometer is the primary sensing device used to determine the appropriate conditions for initiating the various modes. However, some of the RTD's are used to initiate the various modes if appropriate.

3.2 SYSTEM OPERATION

The system design objective is to maximize utilization of solar energy to meet building heating and cooling demands. Since the primary building load is cooling, the priority for use of available solar energy is first to drive the chillers whenever the solar isolation is sufficiently high, and second, to provide heating energy to the building.

The building interior is divided into twelve zones, each of which has a thermostat and a hot and a cold fan coil unit. Since each of the zone thermostats may call for heating or cooling for that zone, heating and cooling of the building can be satisfied simultaneously. An economizer which uses outside air to cool the building is also included in the ventilation system.

There are four independent fluid loops in the system mechanical arrangement shown in Figure 2. The primary loop in the system is the collector loop which, depending on the position of value V_1, is connected with either the primary side of the heat exchanger (HX-1) or the water chillers. The second basic fluid loop is the chilled water loop consisting of the chilled water side of the chillers, the cold storage reservoir and the cold fan coils in the building. The third loop is the cooling tower loop, and the fourth loop is the hot storage reservoir loop which communicates thermally with the rest of the system through heat exchanger HX-1. This heat exchanger has two tube bundles and a shell circulation loop energized by pump P_{10}. The circulation loop allows thermal communication between the two tube bundles. The primary bundle communicates with the hot fan/coils by way of the boiler loop. For example, solar energy may be used to meet the building heating demand and any excess may be simultaneously stored in the hot reservoir. The secondary tube bundle in HX-1 may also be used to heat domestic hot water with solar energy via heat exchanger HX-2.

In the mechanical arrangement shown in Figure 2, when valve V_1 is in the B $\rightarrow$ AB position, solar energy is used to drive the absorption chillers to produce chilled water; when valve V_1 is in the A $\rightarrow$ AB position, solar energy is used to produce hot water for heating the building and/or hot storage. These two pumping loops are interconnected to an auxiliary boiler loop used as a backup energy source for heating and/or cooling when direct or stored solar energy is unavailable.

There are three primary modes of solar system operation referred to as no, low and high solar insolation modes. In mode 1, when there is little or no solar energy available, the building is heated and/or cooled either from storage or the auxiliary boiler. Mode 2, the low solar mode of operation, is initiated when the solar flux is sufficiently great to provide efficient building heating and hot water storage, but is insufficient to drive the absorption chillers. In general, the system operates in this second mode during most of the winter, and also in summer during the early morning and late afternoon hours. Mode 3 is initiated when the solar insolation is adequate to provide efficient firing of one or both of the absorption cycle chillers. The active periods for mode 3 center about solar noon in summer.

3.2.1 No Solar Mode

The system operates automatically in the No Solar Mode when the pyranometer senses solar insolation less than 140 Btu/hr-ft^2 and/or collector plate temperatures are less than 140°F. To meet building heating demand from the hot storage reservoir, pumps P_2, P_3, P_9 and P_{10} are started. Under these conditions, hot water is drawn from the top of the hot reservoir and transferred across HX-1 sending energy into the boiler loop. Modulating valve V_3 keeps the inlet temperature to the hot fan coils at 110°F by regulating the flow of energy from the boiler loop to the hot fan coil loop.

This transfer of energy continues as long as the building heating demand exists, or until the reservoir energy is depleted. When the temperature at the top of the reservoir falls below 115°F, building demand can no longer be satisfied and the natural gas-fired boiler is switched on.

Domestic hot water demand is satisfied in a manner similar to that for heating demand. Whenever the hot reservoir has a high enough temperature and the boiler is not firing the chillers, energy is transferred from the hot reservoir. Otherwise the boiler is used as the source of energy.

DHW demand is signalled when the domestic water circulation temperature drops below 120°F. Valve V_7 then diverts some of the hot water in the boiler loop through HX-2, thereby boosting the domestic water temperature.

Building cooling demand is met with energy from the cold storage reservoir by starting P5. Since this is a stratified tank, chilled water is drawn from the bottom of the tank where it is coldest and deposited on the top of the tank on its return from the cold fan coils. To insure that stratification of the tank is preserved during period of light load, valve V_9 prevents the return of water to the top of the tank until enough cooling energy has been removed to raise its temperature to 55°F.

If the temperature at the top of the cold reservoir rises above 55°F while in the no solar mode, the boiler comes on to fire the absorption chillers. Under these conditions pumps P_4, P_6, P_7, P_8 and P_9 are turned on. Relatively warm water is drawn from the top of the reservoir, lowered in temperature by the chillers and placed on the bottom of the tank.

Because of the piping arrangement, the hot reservoir cannot be used while the boiler is firing the chillers. Any heating demand under these conditions must be met by the boiler (simply by starting P_3). Any cooling demand is satisfied by the cold reservoir, as before.

3.2.2 Low Solar Mode

The system operates in the Low Solar Mode of operation when the solar insolation is between 140 Btu/hr-ft^2 and 230 Btu/hr-ft^2 and/or the collector plate temperature is between 140°F and 195°F. In this mode solar energy is collected by turning on collector loop pump P_1. The collector flow in this mode passes through the primary side of heat exchanger HX-1.

Space heating or DHW demand is satisfied by opening valve V_2 which allows the boiler loop access to the heat exchanger. By turning on pump P_9 the system transfers energy from the collector loop to the boiler loop where it can be used to satisfy DHW demand. Heating demand can also be met by bringing on pump P_3 which draws energy out of the boiler loop and into the hot fan coils in a manner similar to that in No Solar Mode.

If the outlet temperature of the collector arrays (measured after the ballast tank) rises 10° or more above the temperature of the hot storage reservoir, pump P_2 is started to exchange energy from HX-1 to storage. Building cooling demand in the Low Solar Mode is supplied from the cold storage reservoir, the same as in No Solar Mode. The boiler can also come on in this mode to operate the chillers in order to lower the cold reservoir top temperature below 55°F.

3.2.3 High Solar Mode

Solar insolation in excess of 230 Btu/hr-ft^2 and/or a collector outlet temperature (measured after the ballast tank) greater than 195°F will initiate the High Solar Mode of operation. Under these conditions valve V_1 is switched to the B $\rightarrow$ AB position, thereby stopping energy transfer through the primary heat exchanger. The fluid is allowed to circulate through the system under no load until the collector outlet temperature reaches 210°F. When this condition is achieved, the control system energizes one chiller via pump P_6. If the collector outlet temperature continues to rise to 220°F, the control system energizes the second via pump P_7. Pumps P_8, P_4 and the cooling tower are activated whenever either chiller unit is in operation. Chiller operation will continue until the collector output temperature falls to 195°F at which point the system will switch into Low Solar Mode.

Heating and domestic hot water demand are met in the High Solar Mode by diverting the chiller exit water into the boiler loop by the use of pumps P_9 and P_3. To control excessive collector output temperatures

(230°F or greater) energy can also be diverted into the boiler loop where it is transferred across HX-1 into the hot storage reservoir. The pumps operating to accomplish this objective are P_2, P_9 and P_{10}.

Cooling demand is met by drawing chilled water, which has been deposited at the bottom of the cold reservoir by the chiller into the cold fan coils and then returning it to the top of the reservoir where it acts as a supply for the chillers.

Section 4

DATA ACQUISITION SYSTEM

4.1 INTRODUCTION

To meet the performance monitoring and reporting requirement as contained in the original NSF, and later ERDA, contract, a Data Acquisition System (DAS) was designed for the Santa Clara Community Recreation Center Solar Heating and Cooling System. Design of the DAS was undertaken by the Lockheed Palo Alto Research Laboratory as part of its overall design work on the project. The DAS provides the information necessary for evaluation of the solar energy system design including the performance of the solar powered absorption cooling.

The complexity of the solar energy system dictated that a DAS with real-time data reduction capability be employed. The Hewlett-Packard Co. (HP) became involved in the project and agreed to donate for one year a computer-based system with extensive I/O (Input/Output) capabilities. This system gives the DAS the computational power and core storage necessary to perform real-time data reduction. Some parts of the system were leased from Hewlett-Packard. After the one year loan period was over, the computer system was purchased from Hewlett-Packard by the City of Santa Clara.

The next three subsections discuss the DAS components and their operation within the system.

4.2 DATA SYSTEM COMPONENTS

The data system is responsible for gathering information from the solar-powered heating and cooling system in order to perform performance calculations. The heart of the system is a computer controlled data acquisition system which is fed data from a variety of sensors. Several water flow sensors are also part of the data system, but do not feed data directly to the computer. The measured water flow rates are used in the real-time data reduction program.

4.2.1 Digital Hardware

Computer and related equipment manufactured by Hewlett-Packard (see Figure 3) includes:

- ° 21MX Computer which is the CPU (central processing unit) containing 24 K core storage and executive hardware.
- ° 12768A Mainframe which contains printed circuit cards that make up the 2313 Analog/Digital Converter. It translates voltage signals into digital values for input to the CPU.
- ° 12769A Power Supply which provides power to the 2313A/D converter.
- ° 6940B Multiprogrammer which contains Event Sense input cards and controls their interaction with the CPU.
- ° 2748B Tape Reader which reads from punched paper tape to the CPU.
- ° 2895B Tape Punch which outputs data from the CPU to punched paper tape.
- ° 7970B Digital Tape Unit which inputs or outputs information to/from the CPU on magnetic tape.
- ° 2640A CRT Terminal which is an interactive display providing input/output between the CPU and the operator.
- ° 9866A Thermal Printer which prints all information stored in the CRT memory when commanded from the CRT.

4.2.2 Analog Equipment

The analog equipment consists of the following:

- ° PRT (Platinum Resistance Temperature Sensors) - 100 Ohm sensors manufactured by Hy-Cal Engineering for measurement of fluid and air temperatures (83 total).
- ° Hy-Cal ESD 9025-C-85-B Resistance bridge which translates the temperature proportional resistance of the PRT's to a differential voltage.
- ° Eppley Pyranometer, Model PSP, which measures global sun and sky radiation.
- ° Wind Translator, Weathermeasure W101-P-DC/360, which measures wind direction and velocity.

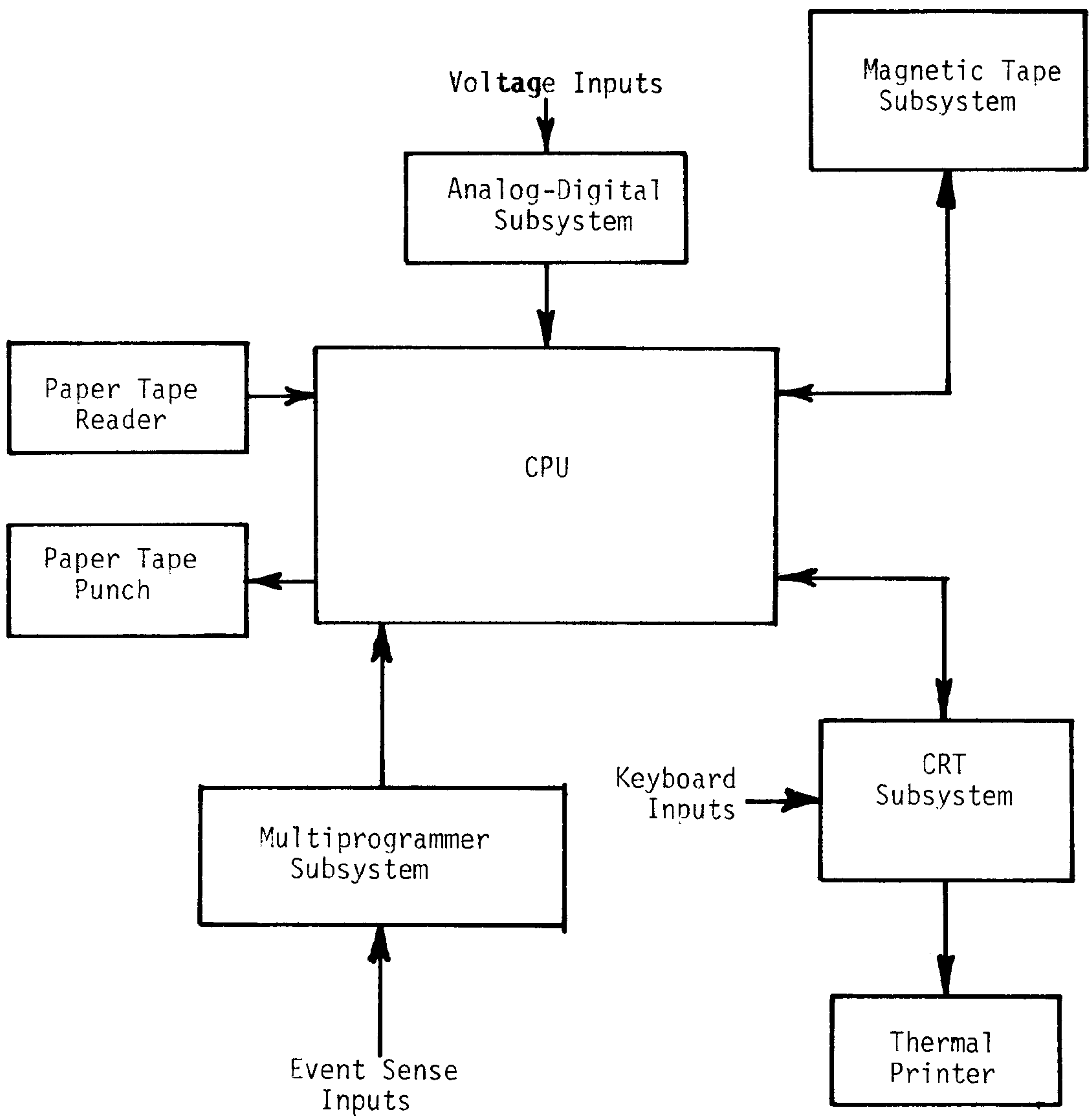


Figure 3 - Computer Hardware Interconnections

4.2.3 Flow Sensors

The following flow measurement devices have been installed in the system. They are used to measure the flow rates required as constants by the DAS software.

- ° Annubar Sensor, a pitot tube arrangement, which measures the velocity head of the fluid flow.
- ° Sparling Flowmeter, turbine type, which is installed in the collector loop on discharge side of pump P_1.

4.3 HARDWARE INSTALLATION AND DESCRIPTION OF OPERATION

4.3.1 Computer Hardware

The computer system is responsible for inputing, converting and storing solar energy system and building data and performing on-site, real-time calculations of performance. The resulting information can then be displayed on the CRT terminal, printed on the thermal printer for hard copy or stored on magnetic tape.

The computer hardware can be conveniently divided into the CPU (central processing unit) and four major subsystems as indicated in Figure 3. The central processing unit consists of the digital hardware necessary to execute programs, store results and control subsystem operation. The CPU is a RTE-C (Real Time Editor Core based) operating system with 24K words of memory.

The CRT (cathode ray tube) subsystem consists of a CRT display and keyboard. The keyboard is used for program formulation, program control and operating system control. The CRT display is used primarily for real time display of system parameters for observation by supervisory personnel. Associated with the CRT subsystem is the thermal printer. This device makes a hard copy of the contents of the CRT display as a result of a command from the keyboard.

The analog-digital subsystem consists of a number of low level and high level voltage multiplexer cards tied into an analog to digital converter. The 110 channels of sensor voltages are scanned once a minute and converted to digital values which are input to the CPU.

The multi-programmer subsystem is a programmable input/output interface unit designed to free the processor from constant monitoring of external conditions. The Event Sense option is being utilized to monitor changes in status of a variety of solar system devices (pumps, valves, etc.). When one of these devices changes state, the multiprogrammer sends an interrupt signal to the CPU which schedules an update program.

The fourth computer subsystem is the magnetic tape storage unit. This device can be used for the storage of daily performance totals and/or real time experimental results. The magnetic tape is taken to the University of Santa Clara computer center where its stored data is processed further and is transferred to hard copy storage.

4.3.2 Transmitting Data Sensors

Approximately 154 data sensors signals are gathered to provide information to the computer about virtually all aspects of the solar-powered heating and cooling system operation. The signals can be classified as follows: low level (800 mv. dc max), high level (10.24 volt dc max.) and on-off (resistance greater than or less than 10 ohms.)

The bulk of the low level signals come from temperature sensors. There are a total of 83 PRT sensors throughout the system, the first thirty of which are used for water temperature measurements in either the piping or water storage tanks. Locations of these sensors are given in the sketch of the system shown in Figure 2. In this figure data sensors are designated by the letter "D" followed by a subscript. Control sensors are designated by the letter "T".

The next 33 PRT sensors are located in the air ducts throughout the building. A typical zone duct arrangement can be seen in Figure 4.

The remaining 20 PRT sensors are mini-sensors used to measure temperatures at various locations throughout the collector array. The specific locations of these sensors will vary since they can easily be moved depending on the information desired.

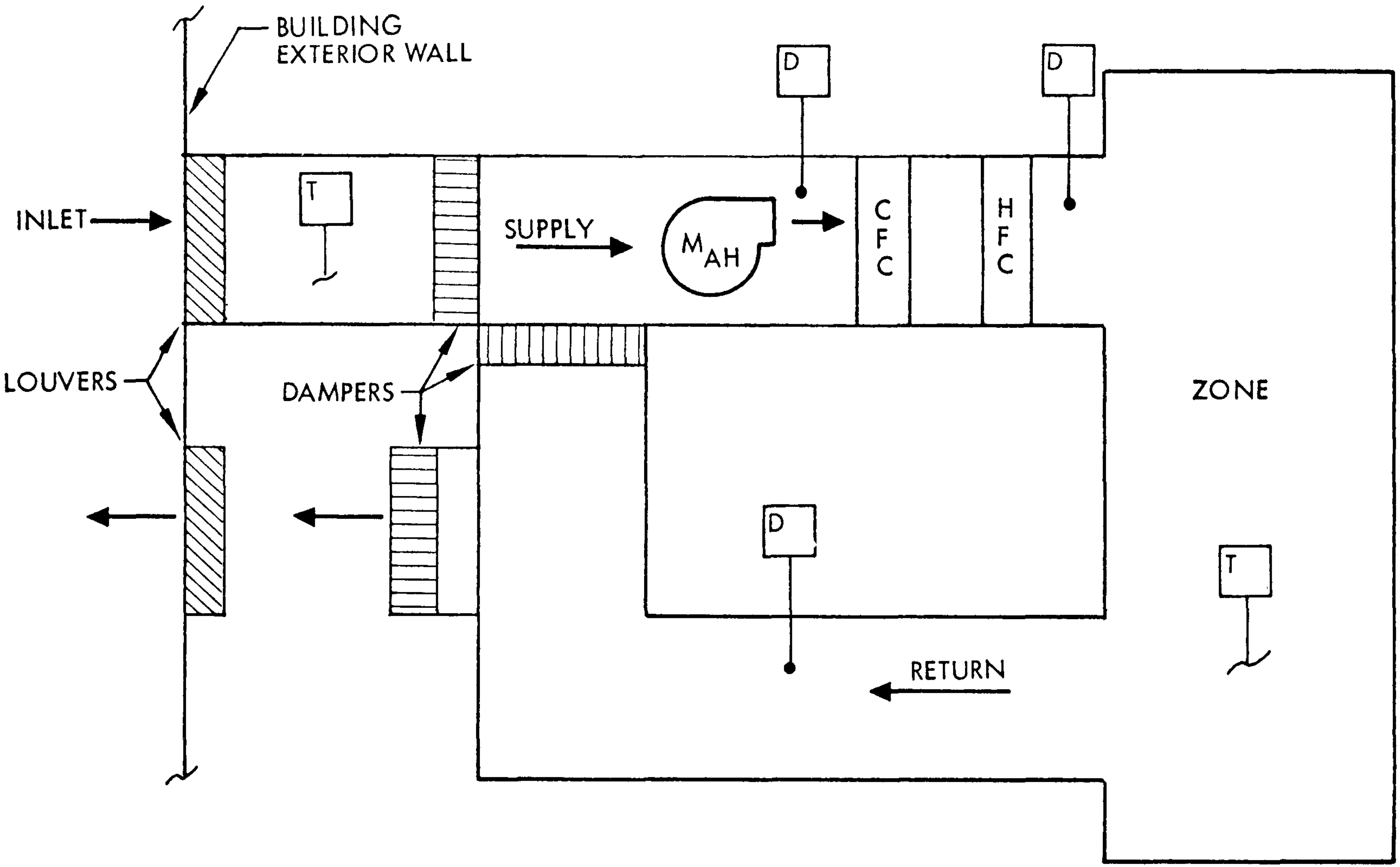


Figure 4. - Typical Zone Duct Arrangement

With the exceptions of the mini-PRT sensors and those PRT sensors in the storage tank, the sensors are ceramic encased, three-wire PRT's with an outside diameter of 3/16 inch . These sensors are mounted by insertion into a stainless steel well which projects approximately 7 inches into the liquid or air flow.

The PRT sensors in the two water storage tanks are also ceramic encased, three-wire PRT's, but with an outside diameter of 1/8 inch. These sensors have extra long leads in order to reach the junction box located in the neck of the tank. Mounting is accomplished by threading the sensor into copper tubing, with a sealed cap on the end, which extends from the sensor position inside the tank to the junction box in the neck of the tank. PRT sensor positions in the cold water storage tank are indicated in Figure 5.

The mini-sensors are the only group that is inserted directly into the fluid stream. Consequently, these sensors are metal clad, small diameter (1/8 inch) and are of such a length (6 inches) as to extend through a Pete's Plug fitting into the fluid. To allow the mini-sensors to be shifted to various locations in the collector array (and to allow pressure measurements to be made), Pete's Plug fittings have been installed throughout the system. Installation of the mini-sensor at a specific location simply involves insertion of the sensor body through the rubber seal of the Pete's Plug and down into the fluid stream.

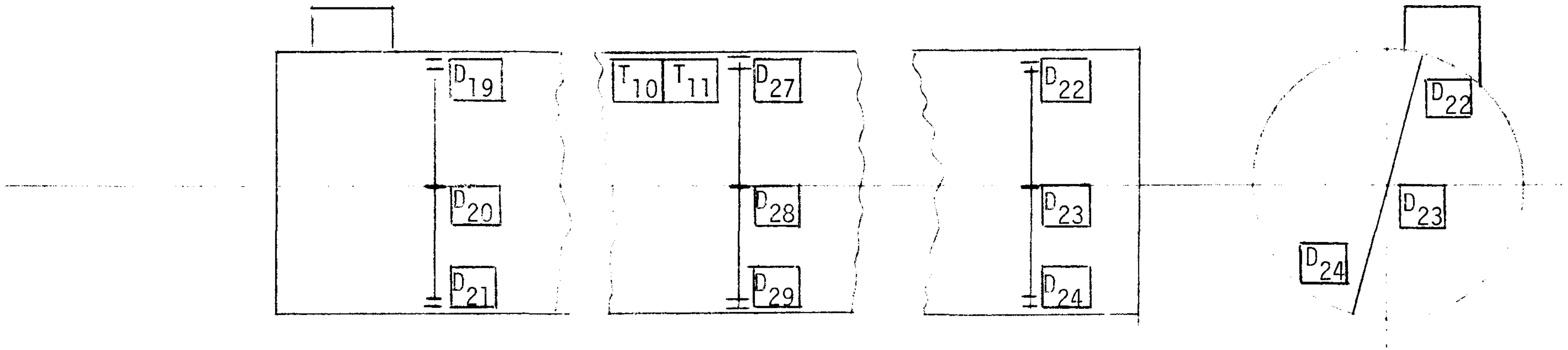
Since the operating characteristics of PRT sensors involve a change of resistance with temperature, a balancing bridge arrangement is necessary to give a temperature proportional voltage. This voltage is then measured by the analog-to-digital equipment and sent to the computer. A self contained bridge unit with provisions for handling 85 three-wire inputs is used. Each sensor is connected to a separate bridge network which has calibration adjustments to compensate for variations in resistance values and lead wire resistance effects.

Also among the low level signals is the measurement of the solar intensity by a pyranometer. This instrument is designed for the measurement of global sun and sky radiation and develops an emf of 9.03 x 10^{-6} volts/(watt/meter^2.) It is located in the plane of the collectors, at the top edge of the wooden collector-supporting structure on the flat roof.

The high level signals are made up of zone setpoint and temperature readings along with wind information. Zone setpoint information (i.e., the desired temperature in the zone) is relayed to the computer by the control system equipment. This is accomplished by the use of a separate potentiometer mounted on the shaft of each setpoint control. Zone temperature readings are also detected in conjunction with the control system. In this case, the zone temperature signal that is used for control purposes is passed through an amplifier and then to the data system. The purpose of the amplifier is to raise the level of the signal so as to make it easily and accurately measurable by the analog to digital circuitry.

Wind information is gathered by a wind sensor and the associated signal conditioning equipment. The wind sensor is located on the flat roof and measures wind speed and direction. Signals from the wind sensor are fed into the wind translator, located in the data system enclosure, which delivers a calibrated dc voltage to the analog to digital circuitry. Wind speed and direction signals provide voltages which are proportional to the quantities being measured.

The final group of data signals represents the current status of various pieces of equipment in the system. The information monitored in this way includes pump status (on or off), valve positions, boiler status, chiller status, solar mode, loss of system pressure, time clock status and override switch positions. The monitoring is accomplished with a group of relays located in the temperature control panel that have open or closed contacts depending on the status of the piece of equipment. The status of the relays can be detected by the Event Sense equipment located in the HP Multiprogrammer. By monitoring these relay closures,



Longitudinal Sectional View

End View

Figure 5. - Location of Sensors in Cold Water Reservoir

the computer is aware of any changes in the system status due to control system operation.

Also monitored by the Event Sense equipment are the contact closures for the two flow indicators. A transmitting water meter indicates the amount of domestic hot water that is used. Natural gas usage is indicated by a switching mechanism attached to the gas meter. These flow indicators make and break a switch contact for each gallon of water, or five cubic feet of gas, flow. Through the Event Sense equipment, the computer can determine the usage over any desired time period.

4.3.3 PRT Calibration Procedures

Calibration of the bridge circuitry involves the simulation of a PRT temperature sensor by a decade resistance box installed at the sensor connections. By adjusting the decade box according to the resistance temperature specifications supplied with each sensor, the bridge circuit for that sensor can be adjusted until the measurement circuitry indicates a temperature corresponding to that resistance value.

A special group of computer programs is needed for calibration purposes. These programs are known as SET, GAIN and ATOD. Program ATOD gives a listing of the high level and low level voltage signals. Program SET repeatedly samples a desired channel and displays on the CRT the voltage which is measured. Program GAIN is used in conjunction with the above two programs to specify the gain used in the low level measurements. It is set as high as possible without allowing an overflow condition.

4.3.4 Flow Sensors

Annubar flow sensors are located throughout the system to allow measurement of all major flow rates in the system. The computed flow rates are then entered into the performance calculations as constants. Annubar locations are indicated in Figure 2. The corresponding quantities measured are indicated in Table 1. Note that information from the flow sensors is not fed directly to the DAS.

Table I. Index to Annubar Measurements

Annubar No.	Flow Rate Measured
1	West Sloping Collector Array
2	Center and East Sloping Array
3	East Sloping Collector Array
4	North Flat Collector Array
5	South Flat Collector Array
6	Total Flat Collector Array
7	Total Collector Flow Through HX-1
8	Boiler Loop
9	Hot Fan Coil
10	Cold Fan Coil
11	Total Chiller Firing Water
12	Total Cold Water Output
13	Chiller #1 Cold Water Output
14	Chiller #1 Condensing Water
15	Chiller #2 Condensing Water
16	Hot Reservoir Loop

4.4 PERFORMANCE CALCULATIONS AND SOFTWARE OPERATION

A software package was written for the 21 MX central processing unit for control of the input/output hardware of the data system. This software package is responsible for (1) the input of signals from the data sensors, (2) the conversion of those signals to engineering units, (3) real-time calculation of performance, (4) summary calculations for the day and (5) output of information collected and calculated for use on site and at a later time.

To provide the basis for this software package, the RTE-C (Real Time Editor-Core Resident) operating system was chosen. This system was provided by Hewlett-Packard Corp. The purpose of an operating system is to provide the environment in which the user-written programs function. The RTE-C system has some particular advantages which make it well suited for use in the data system.

The most important capability of the RTE-C system is implied in its name. The ability to control operation of the user-written programs in real-time is very useful in the collection and processing of the data.

RTE-C executive software programs may be scheduled to be run at specified times and/or time intervals by the operator or by program demand. This feature is employed in the periodic scans of the data sensors, the totaling of the day's calculations and initialization for the next day at midnight.

Another important feature of the RTE-C operating system is the ease of control over input and output. With the Hewlett-Packared supplied executive software and I/O drivers, all input and output can be accomplished through user programs written in FORTRAN. This makes writing of programs relatively straight forward.

For example, the multiplexed input of data signals from the analog/ digital converter was accomplished by one subroutine call written in FORTRAN.

One specific feature of the I/O control is called the Event Sense Mode. In this mode, any change in the status of the 48 channels of on/off type information connected (through the four Event Sense cards) to the multiprogrammer causes the program ALARM to be run. In this way any change in status of the boiler, the chillers, the pumps and the valves can be sensed instantly without continuous scanning. When the change occurs, the program ALARM inputs the new status of the 48 channels and updates information stored in the computer.

Using the data collected by employing the I/O features mentioned, the computer makes and summarizes real time performance calculations. Doing calculations in real time is an advantage because of the size and complicated nature of the solar energy system. To make calculations as detailed as those now made in real time, a great volume of temperature and on/off status data would have to be stored. Real time calculations are made in the following way:

A scan of the voltage sensor signals (temperature, weather, pyranometer) is made at one minute intervals (or 5 minutes when no devices are active) by the program GET. The signals are converted to the appropriate engineering units from millivolt signals. The temperature conversions are made using an equation fitted to the resistance vs. temperature curve for each PRT. All others are based on conversion constants.

Various energy flows through the solar energy system are then calculated for the interval just passed. Because flow rates are entered as constants, the two primary variables in the energy balance calculations are temperature differences and lengths of time of operation of devices. Changes in density and specific heat with temperature are also accounted for. Temperatures are made available by the immediately previous scan. Lengths of operation can be noted by observing the changes in the on/off states. Many of the energy calculations depend on a combination of on/off states. To account for this, the program ALARM, which runs upon the Event Sense Mode call, uses the on/off status inputs to create an array of on/off states for each of the 100 energy calculations. These indicate whether or not a calculation should be done.

A length of time for each of the energy calculations is then calculated for the interval just passed by the scanning program. When an on/off status change occurs in the middle of an interval, the Event Sense Mode program calculates interim time values for the interval to that point. In this way, changes in operation of the solar energy system may be accurately accounted for.

The program CALC computes the system performance for the interval just completed. CALC also sums these calculations over the day. The time lengths for each calculation are also totaled over the day, providing information on how long the solar energy system has operated in each submode. At midnight the program MNITE is run to complete the totals of performance calculations and make additional calculations of daily performance.

Output, to paper or magnetic tape, of daily totals is accomplished by program LOOK. LOOK also is used for on-site real-time displays of all data collected or calculated. This information is output through the CRT terminal and can be recorded using the thermal printer. The availability of data on-site in real-time proved to be very valuable in operation of the solar energy system. Temperature sensor outputs were used to calibrate control sensors and instant readout of all data sensor outputs allowed the status of system operation to be determined at a glance. This option was especially useful during solar energy system start up and check out.

Daily summaries are taken to the University of Santa Clara where they are converted to hard copy (paper.) They are divided into monthly and seasonal totals. Further analysis of the data is performed at the University.

Section 5
OPERATIONAL EXPERIENCE WITH THE DAS

By the beginning of the summer of 1976 the data sensors and computer hardware had been installed on site. Wiring between the measurement equipment and the data sensors was completed in mid-summer, 1976.

Initial attempts at measuring temperatures with the data acquisition equipment produced inaccurate readings. Conversation with the manufacturers disclosed some unexpected interfacing problems associated with solid state measurement equipment. A characteristic of analog to digital circuitry is that a signal of improper level on one of the channels of the measurement card results in inaccurate readings for all of the signals on the card. Consequently, any disconnected sensor channels cause "blocks" of sensor readings to become meaningless. The problem was solved by grounding any sensor inputs which were not being used, thereby presenting an acceptable signal level to the A/D equipment. Temperature sensor circuitry calibration began immediately and was finished by September ob 1976.

Subsequent conversations with the manufacturer of the bridge circuitry indicated that the decade resistance box which had been used for calibration was not accurate enough for our requirements. The original equipment had adjustments down to 0.1 ohm but for reasonable calibration accuracy, resistance measurements of $\pm$ 0.01 ohms are necessary. A General Radio 1432-T decade resistance box with the required accuracy was purchased and recalibrations were completed in late November.

Natural gas usage figures for the performance calculations were originally to be obtained by logging the gas meter readings once a day. This proved to be inconvenient since daily performance totals were based on a twenty-four hour period starting at midnight and would, therefore, require meter readings at midnight. A more convenient method was found by mounting a small switching mechanism directly to the gas meter which sends a sig for every five cubic feet of gas flow. This device was directly interfaced with the DAS, without any hardware modifications, through the Event Sense System.

Since water and air flow rates are entered as constants into the performance calculations, it is very important that these values be accurately determined. During the Fall of 1976, the G.J. Yamas Co., was asked to balance the water and air flows to design specifications and to provide a report of the results. Water flow rate measurements were then determined from circuit setter pressure drops and pump head readings.

The solar system hardware and DAS software were operational by March of 1977. Initial energy balances indicated major imbalances. Temperature sensor circuitry calibrations were then checked for the first time since November. It was found that most of the sensor circuits had drifted out of calibration by an average of 1°F.

Once the temperature sensor circuitry had been recalibrated, the energy balances were still very inaccurate, so flow rate values were recomputed using Annubar flow measurement devices which were present at some points throughout the system. Major differences (as high as 40%) were found between the Annubar readings and those of the flow balancing report. Therefore, the decision was made to rely exclusively on Annubar readings.

In order to measure all of the flow rates, it was necessary to install more Annubar devices. Also, any of the original installations which were close to valves and elbows were relocated to avoid possible unestablished flow conditions. Improved flow rate measurements were achieved in early July which resulted in reasonable energy balances. Fortunately, previous data can be modified to reflect the new flow rate measurements and all results in this report represent the most accurate flow rate information.

Also during July, as a result of questions regarding variations in collector flow rate with temperature, a turbine flowmeter was installed in the collector flow loop. Flow measurements taken with this meter indicate that there is no significant change in volumetric flow rate as a function of temperature. However, the volumetric flow rate in the collector loop does change with mode of operation. The collector flow rate is somewhat lower in the low solar mode when the flow is through the main heat exchanger than the flow rate in the high solar mode when the heat exchanger is bypassed and the collector fluid goes directly to the water chillers.

Since a constant flow rate had previously been assumed, modifications to the performance calculations were necessary to account for the two different flow rates. This involves dividing the total time of collector operation into the times spent in high and low solar modes. Fortunately, this procedure could also be applied to previous data and is reflected in all results presented in this report.

As a result of the discovery of sensor circuitry calibration drift in March, a close watch has been kept on calibrations. It appears that recalibration is necessary about once a month for accurate results. This is inconvenient and costly as 83 temperature sensors are involved, so an investigation is currently under way to find a better solution to this problem.

Section 6

PRELIMINARY ANALYSIS OF SYSTEM PERFORMANCE

The performance of the Santa Clara Community Recreation Center solar heating and cooling system for the six months, April--September, 1977, is presented in this section. (March data was taken but is not included here because it was during that month that the work to insulate the collector manifolds was still under way. Therefore, the data for that month would not be representative.) It is during these six months that the solar cooling phase of system operation takes place. The following data will show how the system and individual components functioned in providing the cooling energy to meet the building needs. The first subsection discusses the modifications which were made to the data for presentation. The second subsection describes the operation of the system during a clear summer day and a partially cloudy summer day. The third subsection gives detailed monthly performance data for May and August and overall performance data for the six months cooling season of April 1977 through September 1977. The fourth subsection discusses the performance of individual system components. The performance analysis is concluded in the fifth subsection with a comparison of the fossil energy requirements of the building during the cooling season with the estimated requirements of two non-solar systems.

6.1 MODIFICATIONS MADE TO THE DATA

6.1.1 Days Not Included and Adjustments Made

Performance calculation totals for some days during each month were not usable due to DAS equipment or software malfunctions, power failures or heating/cooling system malfunctions. To make the energy calculations for the usable days in each month representative of the full month, the sums of the days used were modified. The modification consisted of multiplying each energy calculation sum (except for thermal reservoir energy changes) by the ratio of the days in the full month to the number of usable days in the month. For example, June has 30 days, 21 of which were usable. The ratio which was applied to the energy sums is therefore 1.429. Daily averages, efficiencies or percentage distributions were not affected by the modification.

6.1.2 Modifications in Data Due to Remeasurement of Flow Rates

Because flow rates are treated as constants in the calculation programs, the changes in known flow rates due to remeasurement required correction of the calculated output. For most of the flow rates this was accomplished by multiplying the appropriate computed output by the ratio of the new flow measurement to the old value.

However, this procedure was inadequate for the collector output calculations because the measured flow rate through the collectors was found to increase when the system switched to High Solar Mode.

The collector performance calculations were first modified to account for the new Low Solar Mode flow rate in the manner described above. In High Solar Mode, there are three distinct sub-modes of operation: (1) one chiller operating, (2) two chillers operating, and (3) circulation to bring loop temperature up. The extra energy collected for the High Solar Mode that was not accounted for previously was estimated from the typical average collector temperature differences during each sub-mode, the increase in flow rates for each of the High Solar sub-modes and the duration of operation in each sub-mode.

6.2 SYSTEM OPERATION DURING TWO SUMMER DAYS

One of the primary advantages of the present data acquisition system is its ability to process, for any given sampling interval, system status signals, system temperatures, performance calculations for the previous time interval and/or running totals of the daily performance calculations. These values can be stored on magnetic tape or displayed on the CRT without interferring with the daily performance calculations.

This ability to study system performance in a "real time" manner allows detailed studies to be made of system response under a variety of transient operating conditions, thereby giving clues to optimization of equipment and setpoints which might not be available from the analysis of daily performance totals. System cooling performance for two full days of operation is presented in Figures 6 through 9. The bulk of the data samples were obtained at twelve minute intervals. A complete list of the performance calculations made in real time is presented in Appendix A.

The days chosen for study were 28 August 1977 and 18 September 1977 and so represent late summer operation with high cooling loads and essentially no heating load. They are also both Sundays, days on which the building heating and cooling fan coil units do not operate until the building is occupied at 2 PM. Therefore, for the days selected the solar system will operate normally until 2 PM by storing hot or cold water energy in the reservoirs. Consequently, the effects of system operation on reservoir temperatures will be more dramatic before 2 PM, since the reservoirs will represent the total load on the system.

Hence, the days selected allow a detailed study of the cold reservoir stratification process since cold water is not directed to the building as would normally occur during weekday operation.

Figure 6 presents the solar insolation available for the two days. The day of 28 August 1977 is a typical summer day for the Santa Clara Valley with clear weather and a peak insolation value of about 300 Btu/Hr.Ft.^{2}.

The day of 18 September 1977 was clear until 10 AM when a group of clouds passed over the building. From 11 AM - 12 Noon the sky cleared and normal clear sky solar insolation prevailed. The sky was partially cloudy during the afternoon.

Figure 7 shows how the collector output temperature* varies over the day. Between the dashed lines on each graph are letters which designate the system operational mode which would affect the collector output temperature.

On 28 August 1977 the collector pump started at about 8 AM. The collector output temperature rose very quickly until, when it was 10° higher than the hot storage tank temperature, energy exchange into the hot reservoir began (9:30 AM).

At 9:45 AM the solar insolation was high enough to activate the high solar mode of operation which stopped heat exchange to the hot reservoir. The collector loop then operated with no load until the output temperature became high enough at 10:15 AM to operate the first water chiller. As the collector output temperature continued to rise, the second chiller unit began operating at 10:25 AM.

The variations in collector output temperature centered about noon are not seen by the chiller units since a 200 gallon ballast tank at the outlet of the collectors serves to smooth out transients.

Direct operation of both chiller units from the collector loop continued until collector output temperatures (after the ballast tank) dropped

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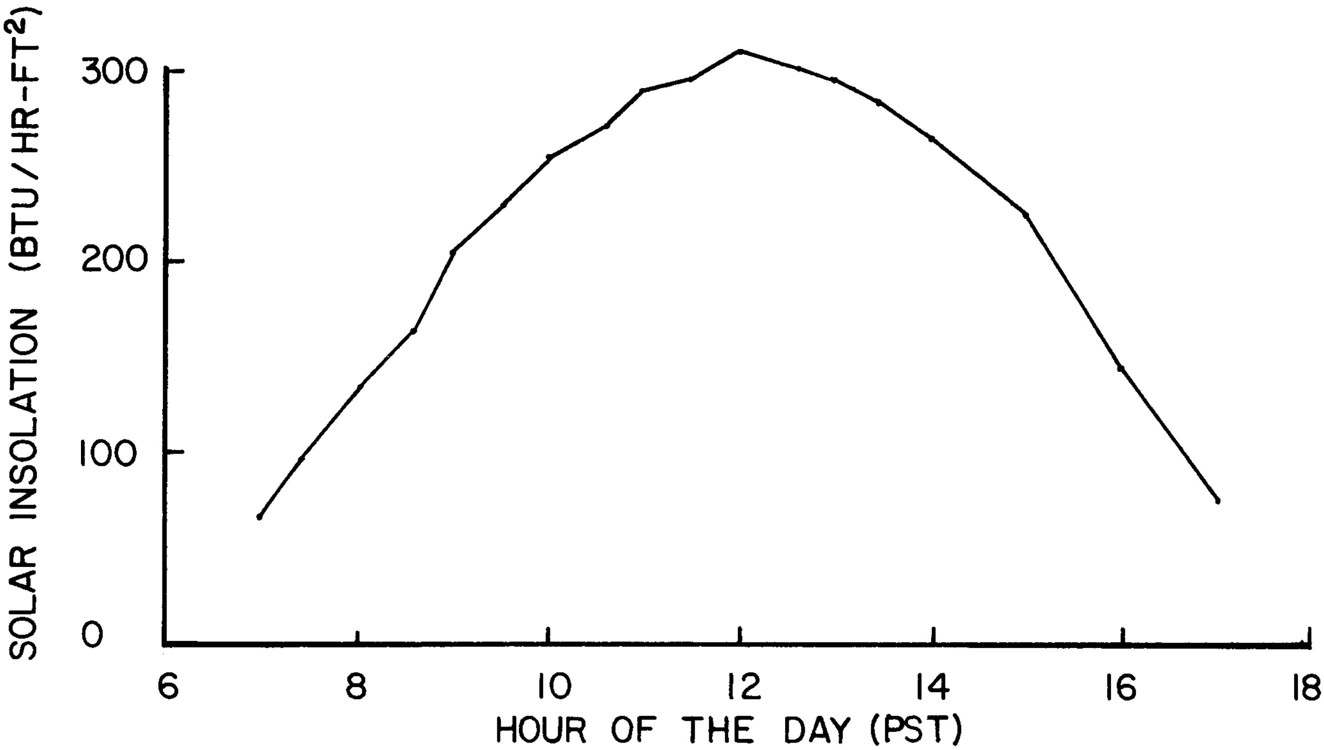
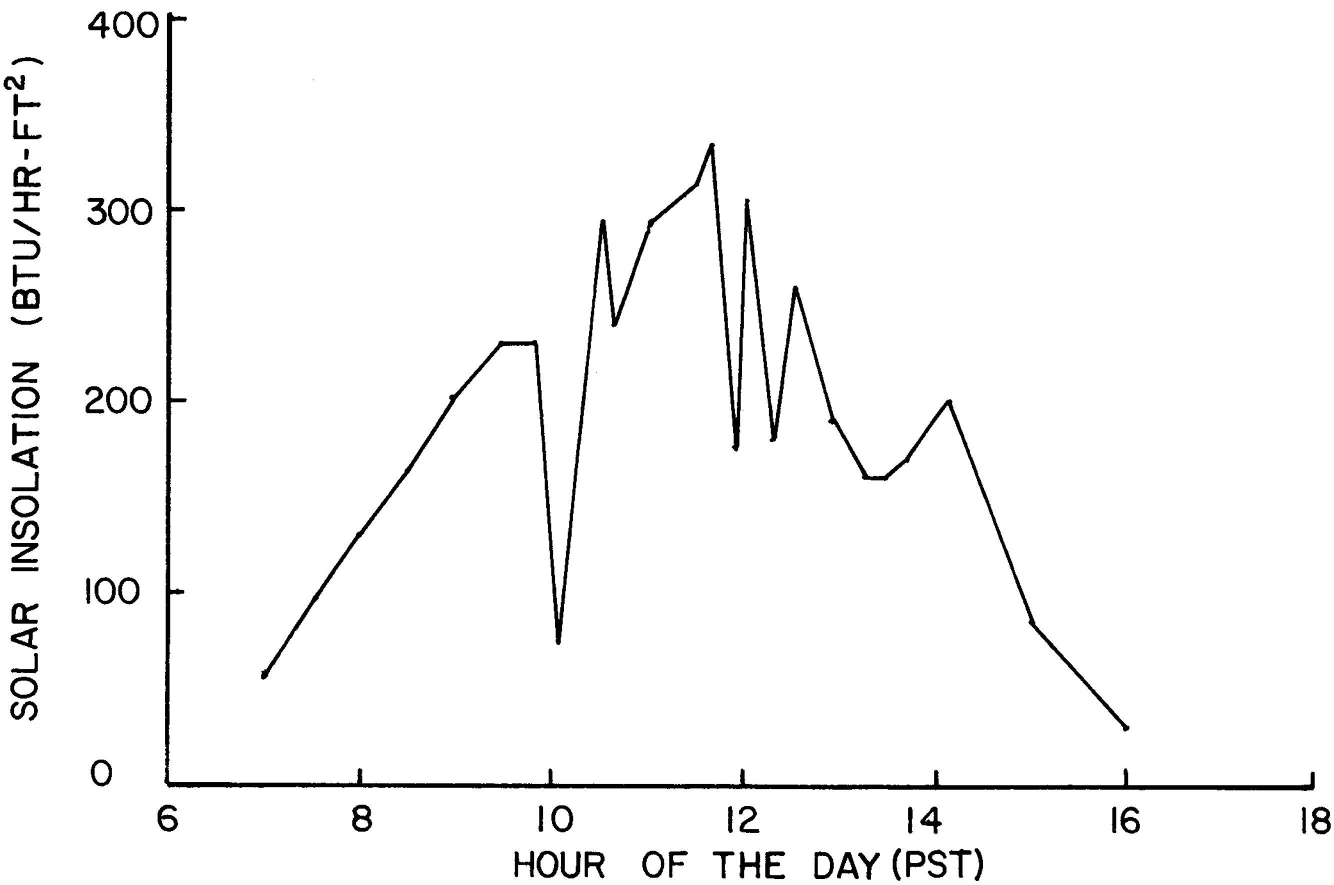
*A weighted average based on collector array areas.



(A) SUNDAY, 28 AUGUST 1977



(B) SUNDAY, 18 SEPTEMBER 1977

FIGURE 6 — MEASURED VARIATION OF SOLAR INSOLATION FOR A CLEAR SUMMER DAY AND A PARTIALLY CLOUDY SUMMER DAY

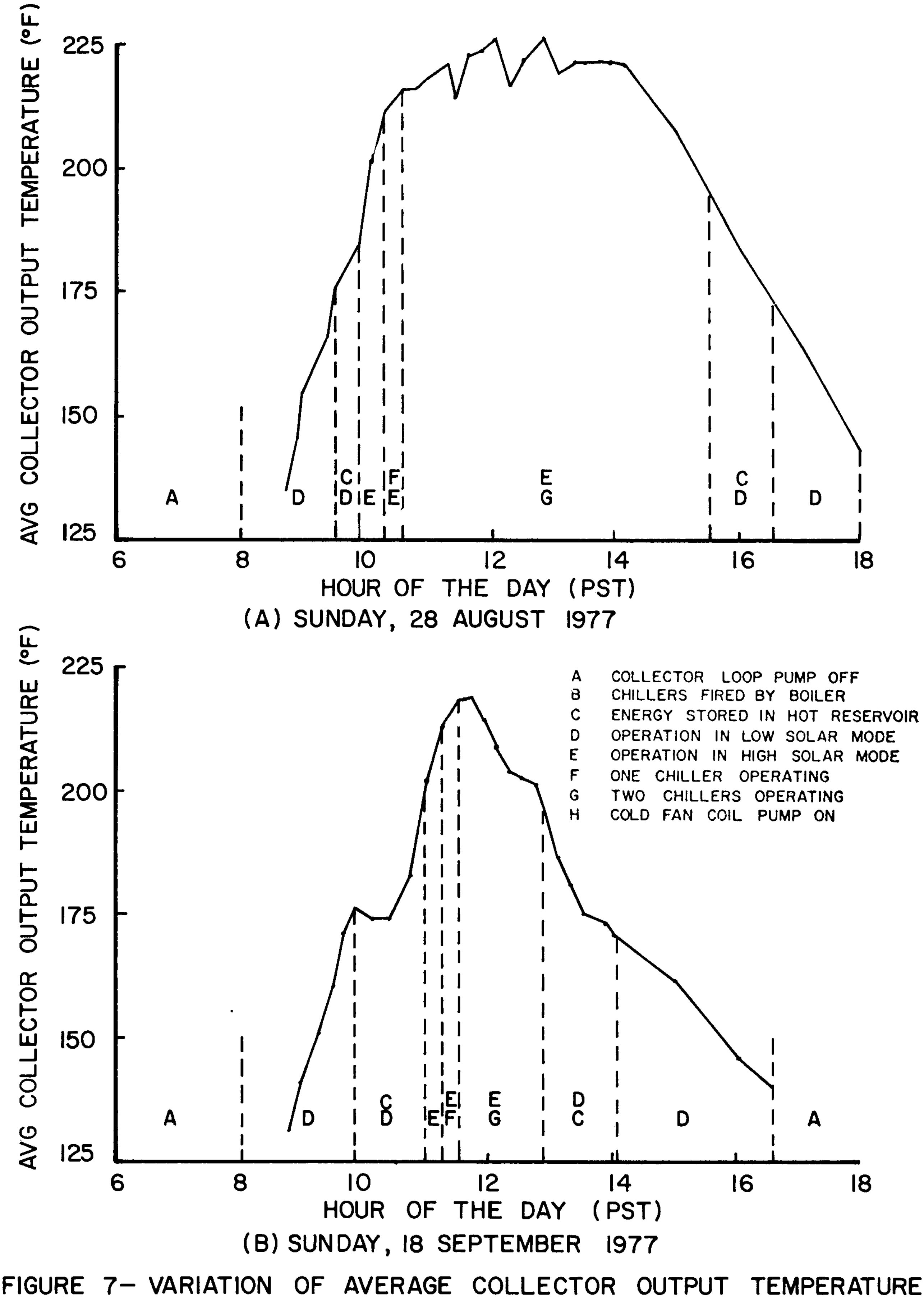


FIGURE 7– VARIATION OF AVERAGE COLLECTOR OUTPUT TEMPERATURE FOR A CLEAR SUMMER DAY AND A PARTIALLY CLOUDY SUMMER DAY

below 195°F at 3:30 PM. At this time the chillers were turned off and the system switched into low solar mode and began storing energy in the hot storage reservoir. Energy storage continued until the collector output temperature approached the storage tank temperature at 4:30 PM. Collector loop circulation continued until the loop output temperature decreased to 140°F, at which time the collector pump was turned off (6 PM).

On 18 September 1977 the system operated in the same modes as on 28 August 1977 but the collector temperature response is quite different. The effect of the dip in solar insolation at 10 AM can be observed in the collector output temperature at 10:30 AM. Also the sharp decline in solar insolation after noon resulted in a short period of chiller operation and rapid temperature fall off in early afternoon.

In the early design stages of the solar project, Lockheed found that for cold storage to be effective a stratification system must be used. Stratification was necessary to insure a source of chilled water (at the bottom of the tank) below 50°F to send to the cold fan coils and a source of warmer water (at the top of the tank) about 55°F to send to the chiller without reducing its capacity.

In Figure 8 an indication is given of the degree of stratification achieved on the two days selected. Top center and bottom center temperatures of the cold reservoir are compared. It should be noted that the temperature swings are somewhat greater Sundays than on weekdays since there is no cooling load until 2 PM.

On 28 August 1977 a relatively high temperature at the top of the tank was present indicating a large cooling load the previous day. The chillers, fired by the boiler, began operating at 8 AM to bring the temperature of the reservoir to its "minimum specification" level of 55°F at the top.

At that time the chillers were drawing water from the top of the tank at 59°F. Since the drop in temperature across the ARKLA units is

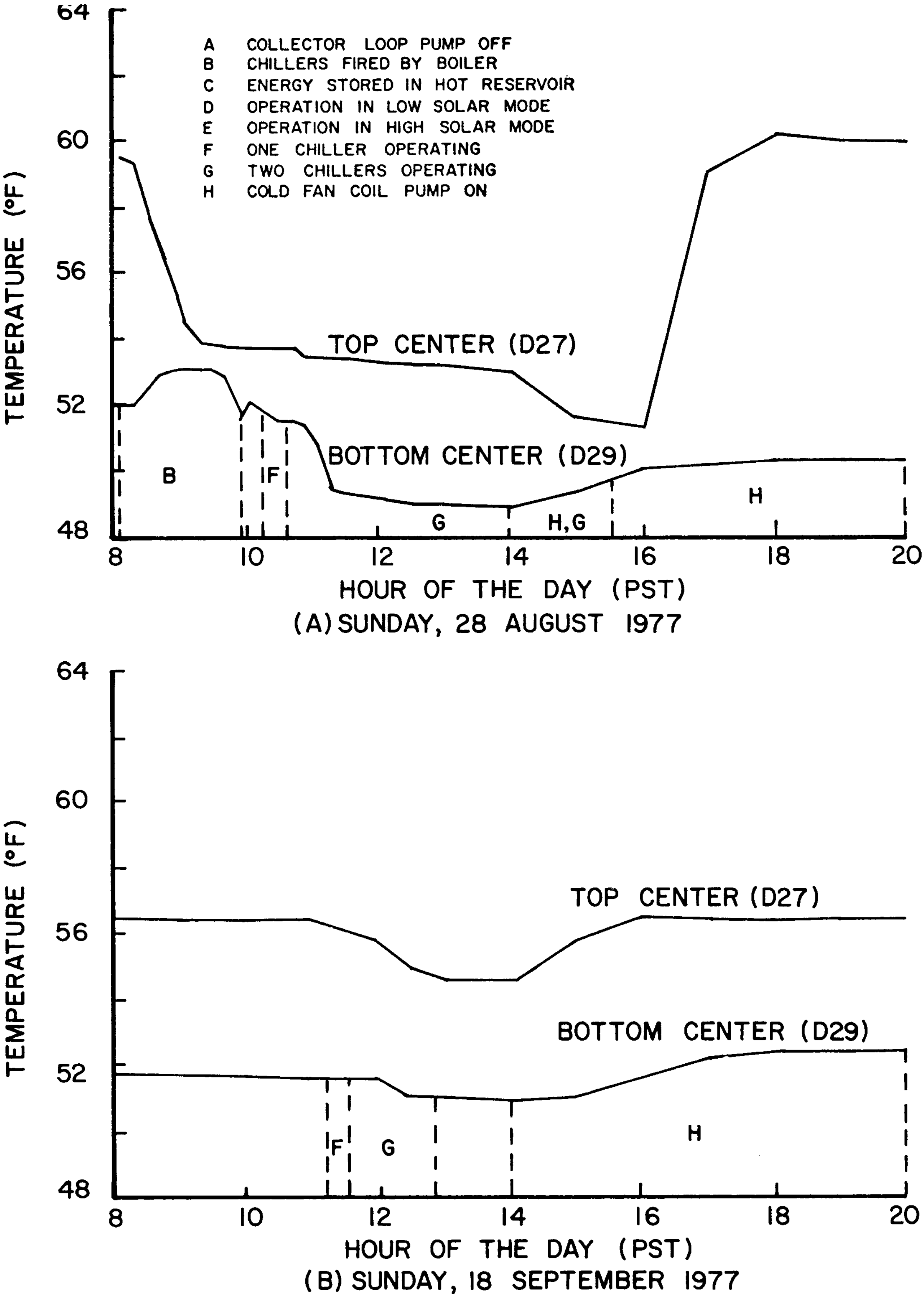


FIGURE 8 - VARIATION OF COLD RESERVOIR TEMPERATURES FOR A CLEAR SUMMER DAY AND A PARTIALLY CLOUDY SUMMER DAY

about 6°F, the temperature of the water coming back from the chillers was about 53°F thereby causing the temperature of the bottom of the tank to rise until about 9:30 AM. At that time, the higher temperature water at the top of the tank had been chilled and deposited at the bottom causing a drop in temperature at the top by upwelling. At 9:45 AM the system switched into high solar mode which stopped boiler-fired chiller operation in preparation for solar fired operation. At 10:30 AM both ARKLA units were in operation pulling water at a temperature of 54° from the top of the tank, dropping its temperature about 6° and depositing it on the bottom causing a rapid decrease in the temperature at the bottom. At 2 PM the cold fan coil pump began to draw chilled water from the bottom of the tank, returning it to the top after it had reached a set temperature of roughly 57°F. This relatively warm water did not cause large changes in tank temperature until 4 PM when the temperature at the top of the tank rose sharply.

The reason for the lag in the temperature history at the top of the tank is that the output of the chillers is nearly equal to the demand of the cold fan coil units. When the chillers were shut down at 3:30 PM, the cold fan coil load was met by water from cold storage which, when returned to the tank, caused a sharp rise in temperature at the top.

On 18 September the temperature at the top of the cold tank is within "minimum specification" so the chillers were not fired until the solar insolation became sufficiently high at 11:30 AM. The top and bottom temperatures of the cold tank then decreased for the hour during which the chillers operated. Since the chillers were not operating at 2 PM when the cold fan coil pump began to operate, the tank temperature began to rise. The magnitude of this increase indicates that the cooling load for this day is much less than that of 28 August 1977.

The hot storage tank temperature history for the two days of interest is presented in Figure 9. The two sensors used for these measurements

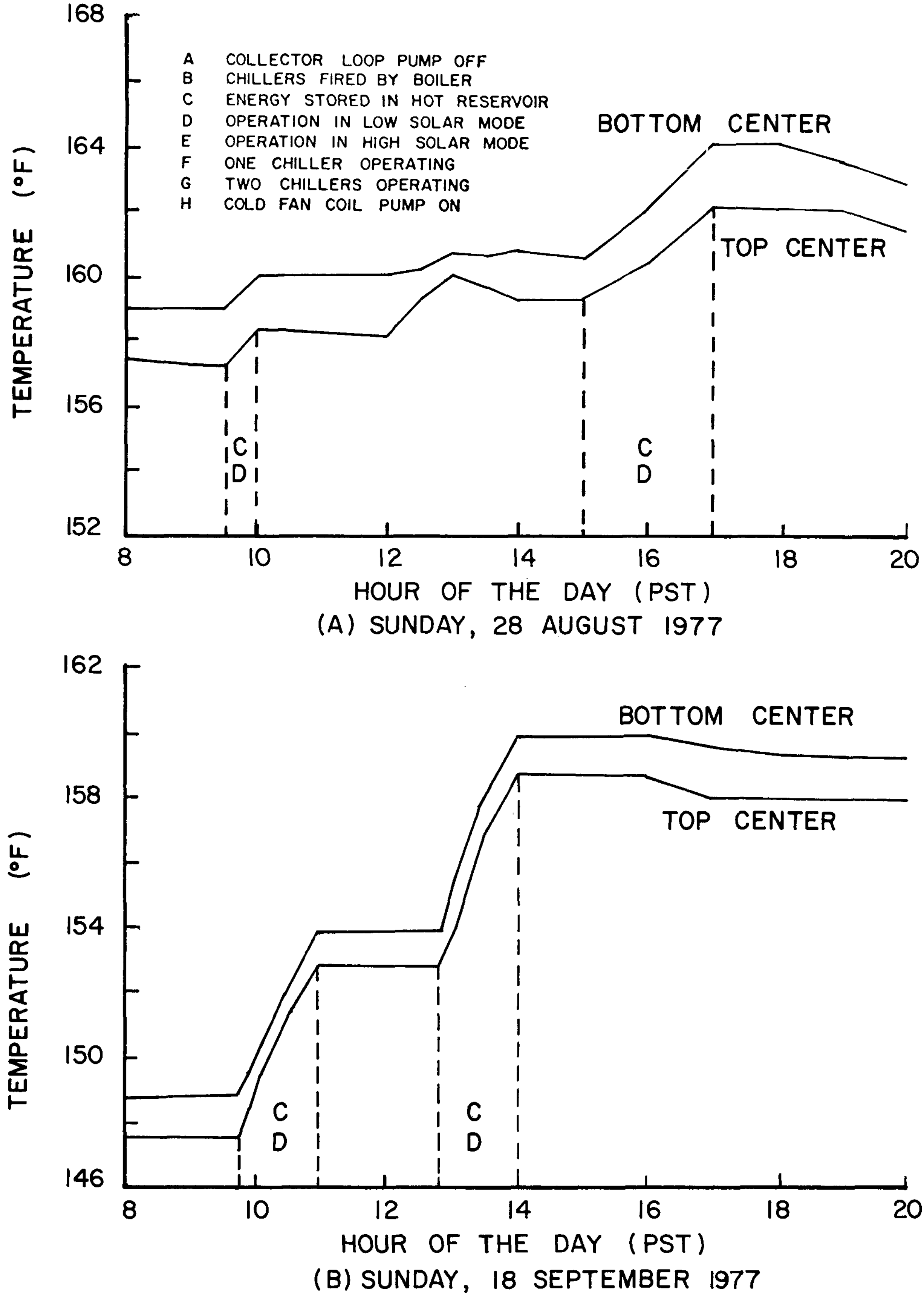


FIGURE 9- VARIATION OF HOT RESERVOIR TEMPERATURES FOR A CLEAR SUMMER DAY AND A PARTIALLY CLOUDY SUMMER DAY

are located in the middle of the tank approximately one foot away from the top and bottom water surfaces. The storage tank is nonpressurized and is vented to the atmosphere. This venting allows an energy loss to the atmosphere which causes the water temperature at the top of the tank to be lower than the water temperature at the bottom of the tank.

The drop in the top tank temperature in the late afternoon gives an indication of the loss rate (approximately 490,000 Btu/day for August.)

6.3 MONTHLY SYSTEM PERFORMANCE DURING THE COOLING SEASON

Weather data for the 1977 cooling season is presented in Figure 10. The response of the building to that weather is shown in Figure 11 which gives the average daily thermal energy requirements of the heating and cooling system for each month and the portions provided by the boiler and by the solar collectors. The heating energy requirement is defined as the measured energy delivered to the hot fan coils. The solar portion of the heating energy requirement is that provided (1) by the collectors directly, (2) by the hot storage tank and (3) by solar heated chiller firing water after it has been used by the chillers (chiller "bleed" heating.) The cooling energy requirement is the firing water energy used by the chillers during their operation. The solar portion is the firing water energy provided by the collectors. Note that it is <u>not</u> the cooling energy delivered to the cold fan coil units. The total energy requirement is the sum of all thermal energy used to provide heating, cooling, and domestic hot water. Domestic hot water load is not shown in Figure 11 because of its small magnitude, typically around 0.2×10^6 Btu/day.

Figure 12 presents the average daily energy delivered by the solar collector array and the boiler. Delivered solar energy is defined as the energy output of the total collector array. Boiler energy delivered is defined as the measured energy output of the boiler loop system. This value does not include line losses in the boiler loop. Figure 12 also shows predicted values for the average daily energy requirement based on results from the original Lockheed computer simulation performed during the design phase of the project. These values were calculated using the weather for CY 1971. Shown at the top of the figure is the ratio between the actual insolation and the insolation values for CY 1971 employed in the model.

Note that the actual insolation measured was higher than the insolation for 1971 yet the measured and simulated collector outputs are approximately the same. This indicates that the collector array performance is slightly lower than expected.

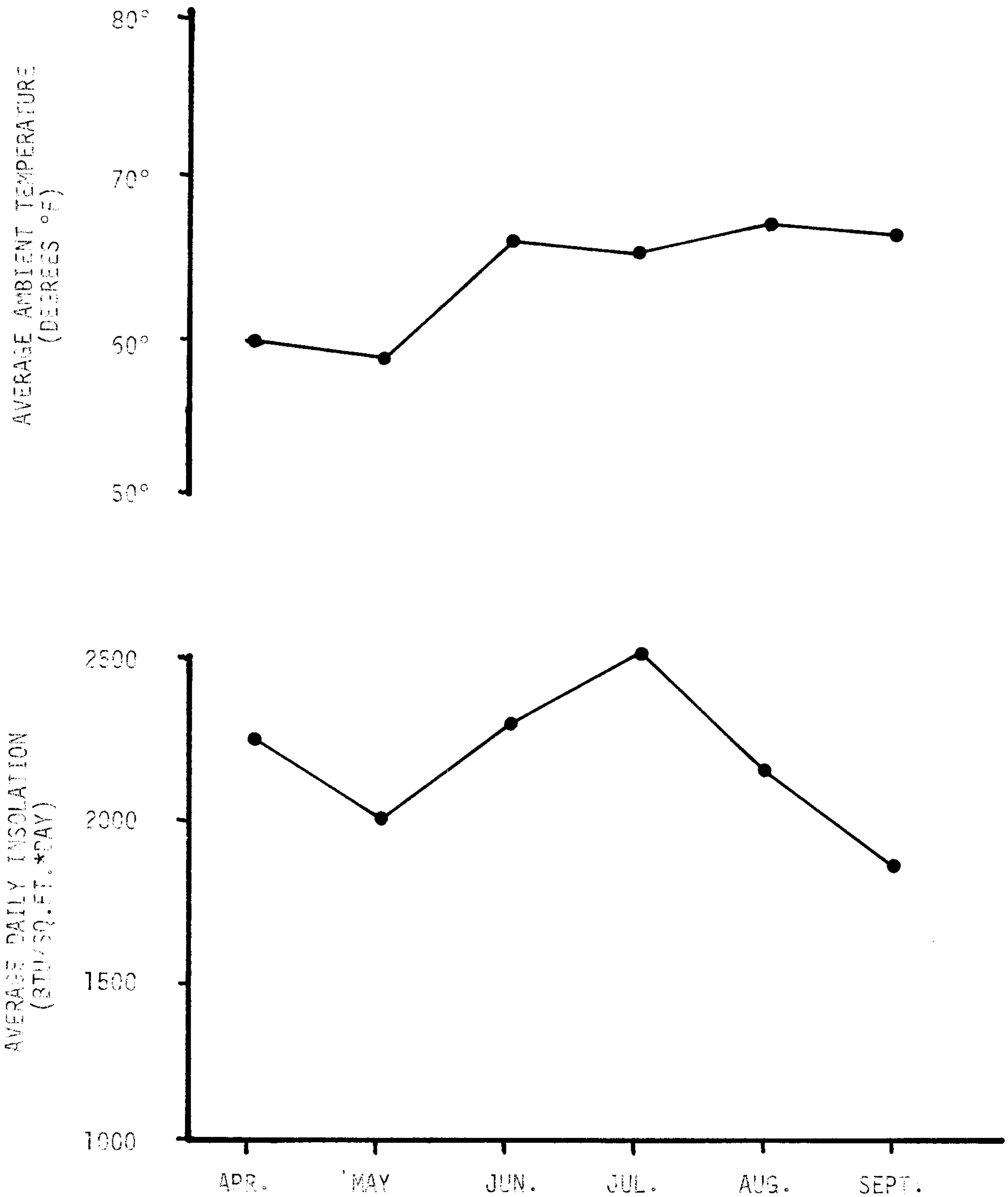


Figure 10. - Insolation and Ambient Temperature Data for the Six Month Period.

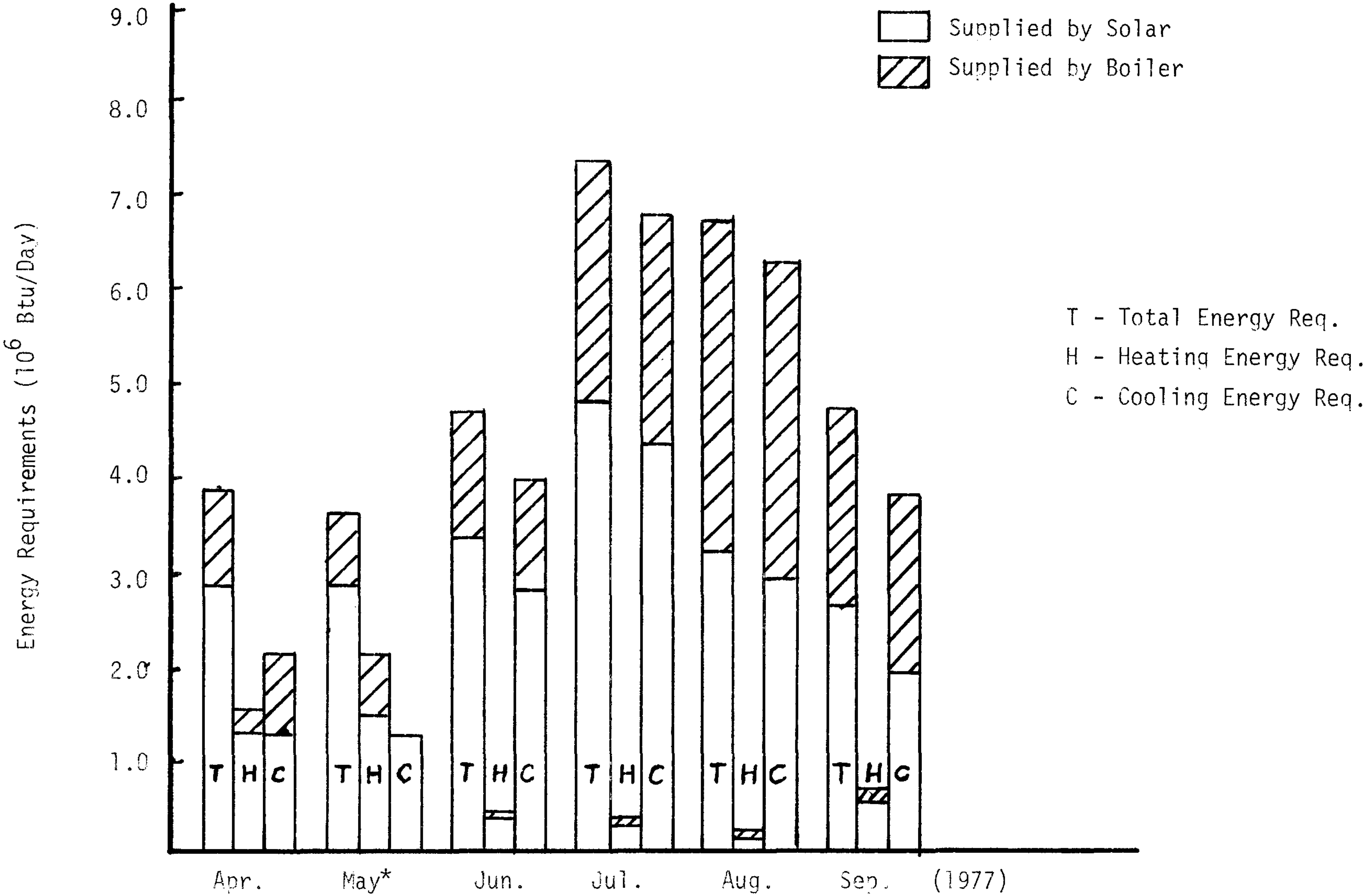


Figure 11.- Average Daily Thermal Energy Requirements for the Santa Clara Community Center during April-Sept., 1977

*Manually locked out boiler for cooling operation because of weather conditions.

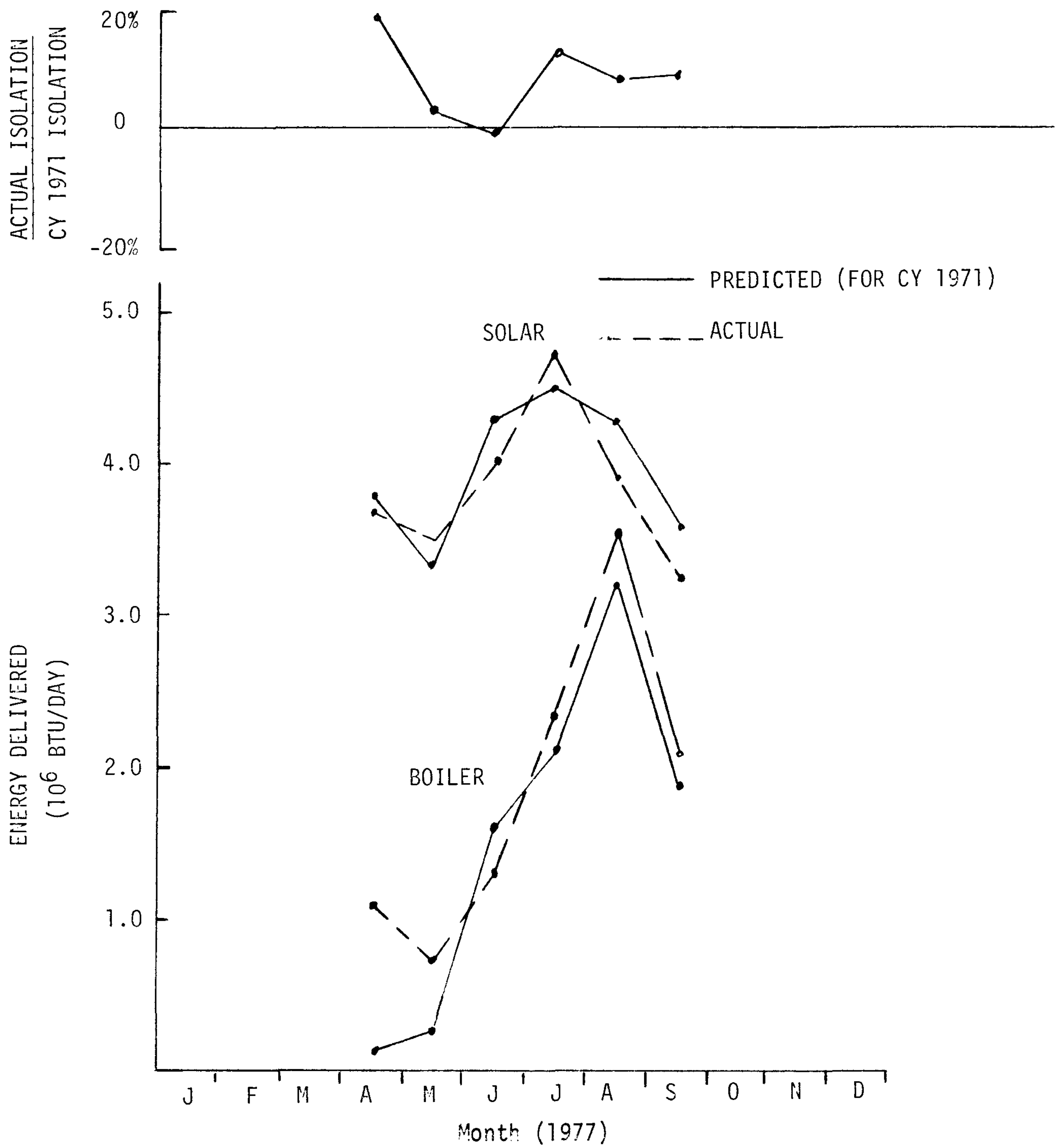


Figure 12. - Average Daily Energy Delivered by the Solar Collector Array and the Gas-Fired Boiler for April-Sept., 1977. Santa Clara Community Center.

The large discrepancy in actual and predicted boiler energy delivered in April is due to an actual hot fan coil load considerably higher than the predicted value. This is shown in Figure 13 which compares measured average daily fan coil loads with those predicted by the Lockheed computer model. The differences between the average daily temperature for 1971 and 1977 are also shown. The fan coils are the heat exchangers within the building's forced-air system which provides heating and cooling to the various building zones. HFC refers to the hot fan coils and CFC refers to the cold fan coils.

Even though the actual CFC load is lower than predicted, the total amount of thermal energy required for cooling is close to the predicted value. This indicates lower than expected chiller performance.

Computer printouts of the system performance for May and August and for the entire six months are presented in Figures 14-16. The terms used in the printouts are explained in Appendix B. Note that the solar energy collected is accounted for to within seven percent. The monthly efficiency of the collector arrays is shown in Figure 17. The monthly efficiency is defined as the ratio of the total energy collected to the total energy incident on the collectors for two time periods: (1) time of operation of collectors and (2) time during which the sun was up. No adjustment for incident angle changes is made to the efficiency data.

An energy balance on the chillers gives the following equation to use with the data presented in Figures 14 through 16.

$$\text{Energy directed to chillers} = \text{Cooling tower energy dissipated} - \text{Cold water energy from chillers} \quad (1)$$

A measure of the accuracy of the energy balance is:

$$\epsilon = \frac{\text{unbalance in equation (1)}}{\text{energy directed to chillers}}$$

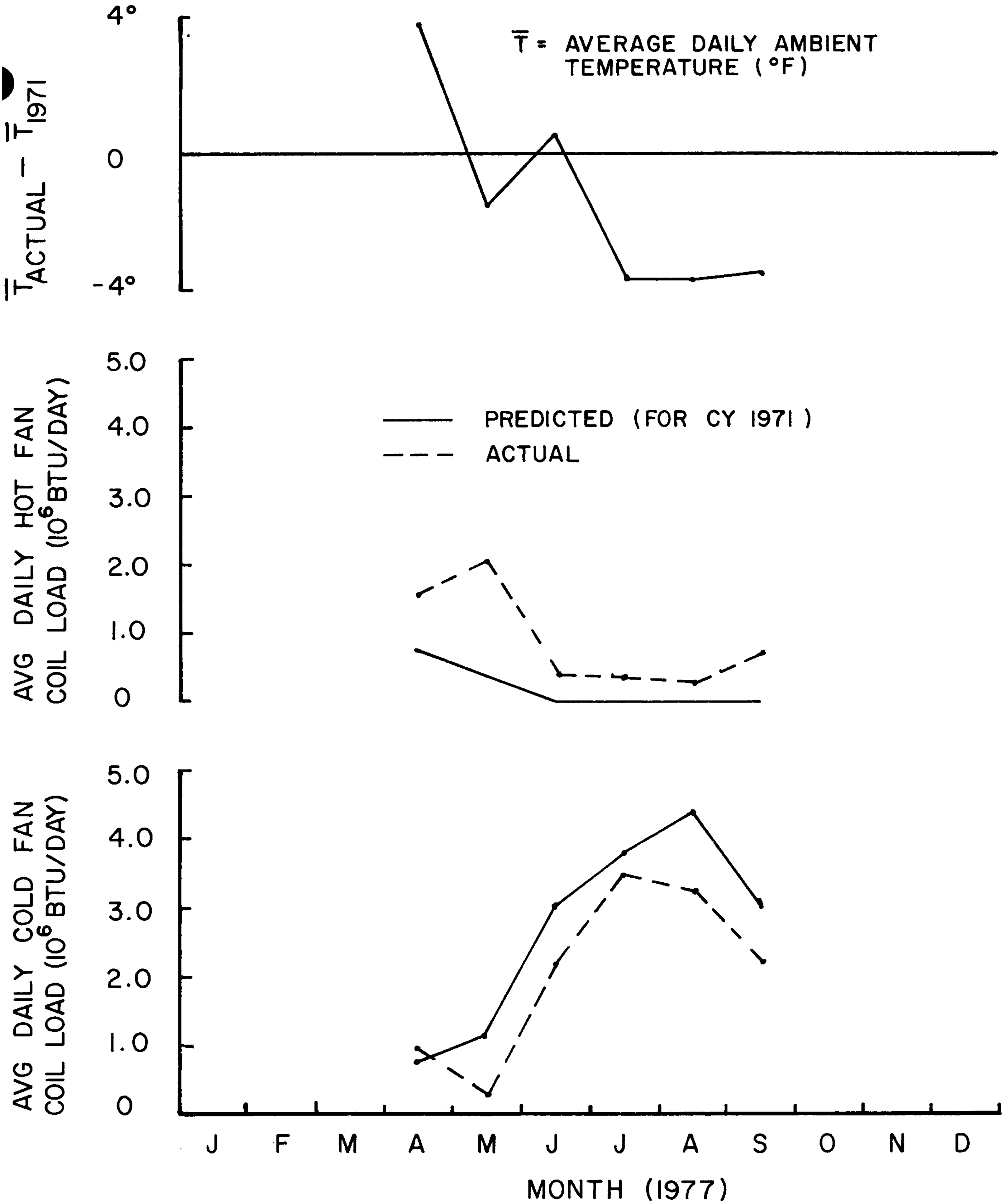


FIGURE 13. AVERAGE DAILY FAN COIL LOAD FOR APRIL – SEPT, 1977. SANTA CLARA COMMUNITY CENTER

SANTA CLARA COMMUNITY CENTER SOLAR HEATING AND COOLING PROJECT

FIGURE 14 MONTHLY TOTALS FOR MAY

NOTE: ALL QUANTITIES, UNLESS NOTED OTHERWISE, ARE GIVEN IN TERMS OF MILLIONS OF BTUS.

* * * * ENVIRONMENTAL FACTORS * * * *

AVG. AMBIENT TEMP. 58.5 DEGREES F

AVG. WIND SPEED .4 M.P.H.

AVG. DAILY INSOLATION 1998.7 BTU/DAY SQ.FT.

* * * * COLLECTOR ARRAY CALCULATIONS * * * *

	INCIDENT SOLAR	INCIDENT DURING OPERATION	ENERGY COLLECTED	EFFICIENCY DURING OPERATION	FRACTION OVER DAY	(TF-TA)/GI AVG.
ARRAY #1	261.78	209.03	68.85	32.94	26.30	.7596E+00
ARRAY #2	177.20	141.50	38.94	27.52	21.97	.7020E+00
SYSTEM	438.98	350.53	107.78	30.75	24.55	.7246E+00

* * * * BOILER CALCULATIONS * * * *

GAS USE OF BOILER AS RECORDED BY METER 41688.8 CU.FT. HEAT VALUE OF GAS USED 43.77 MILLION BTUS

ESTIMATED OUTPUT OF BOILER 30.64 MILLION BTUS, BASED ON 70% BOILER EFFICIENCY

* * * * HOT RESERVOIR CALCULATIONS * * * *

ENERGY OUT	37.65	ENERGY CHANGE	.46
ENERGY IN		LOSS	
BOILER	-.02	MAKE UP WATER	.0000 (. GALS.)
SOLAR	41.66	BOIL OFF	.0000
SOLAR BLEED	1.08	INSULATION	4.0063
SOLAR DUMP	.00		
TOTAL	42.72	TOTAL	4.0063
PREHEAT TO COLLECTORS	.00		

*** * * * DISTRIBUTIONS OF ENERGY * * * ***

PERCENT OF THERMAL ENERGY REQUIREMENT SUPPLIED BY	HEATING	COOLING	FOR DHW	TOTAL
BOILER	33.78	.24	17.11	21.10
SOLAR	66.22	99.76	82.89	78.90

DISTRIBUTION OF SOLAR ENERGY

	HOT RES.	HFC	HFC-BLEED	CHL	DHW	SUM
PERCENT TO	44.61	10.93	1.50	35.03	3.79	95.87

DISTRIBUTION OF BOILER ENERGY (BASED ON BOILER/BOILER LOOP OUTPUT AT 70% OVERALL EFFICIENCY)

	HOT RES.	HFC	CHL	DHW	SUM
PERCENT TO	-.08	71.69	.30	3.56	75.47

DISTRIBUTION OF HOT RESERVOIR ENERGY

	HFC	DHW	PREHEAT	SUM
PERCENT TO	89.53	3.56	.00	93.09

*** * * * TOTAL ENERGY LOADS * * * ***

WATER SIDE HEATING LOAD	65.50	
CFC LOAD	9.88	
DHW LOAD	6.38	
SOLAR ENERGY UTILIZED BY SYSTEM	86.58	(AFTER HOT TANK LOSS)
BOILER ENERGY UTILIZED BY SYSTEM	23.15	
OPERATING ELECTRICAL ENERGY	42.10	12334.3 KWH (FOR OPERATION OF HEATING/COOLING SYSTEM)
TOTAL ENERGY CONSUMED	172.45	(ALL ENERGY INPUT TO HEATING/COOLING SYSTEM)
SOLAR FRACTION OF BUILDING LOAD	.623	(SOLAR FRACTION OF FAN COIL LOADS)
SYSTEM PERFORMANCE FACTOR	.444	(THIS FACTOR IS THE RATIO OF THE TOTAL ENERGY DELIVERED TO THE BUILDING LOAD TO THE TOTAL EQUIVALENT FOSSIL FUEL ENERGY EXPENDED. THIS TAKES INTO ACCOUNT THE FOSSIL FUEL USED TO GENERATE ELECTRICAL ENERGY USED.)

* * * * ABSORBTION CHILLERS CALCULATIONS * * * *

ENERGY DIRECTED TO CHILLERS

SOLAR	37.76
BOILER	.09
TOTAL	37.85

COLD WATER ENERGY FROM CHILLERS

SOLAR	18.43
BOILER	-.03
TOTAL	18.40

C.O.P. OF CHILLERS

SOLAR	.488
BOILER	-.315
OVERALL	.486

COOLING TOWER ENERGY DISSIPATED 61.09

* * * * HOT FAN COILS, DOMESTIC HOT WATER, COLD FAN COILS, AND COLD RESERVOIR ENERGY CALCULATIONS * * * *

ENERGY DIRECTED TO HFC

SOLAR	11.78
BOILER	21.97
HOT RESERVOIR	30.13
CHILLER BLEED	1.62
TOTAL	65.50

ENERGY DIRECTED TO DHW SYSTEM (INCLUDES STANDBY LOSSES)

SOLAR	4.[illegible]876
BOILER	1.[illegible]911
HOT RESERVOIR	1.1960
TOTAL	6.5767

HOT WATER USE 2002. GALLONS

COLD WATER ENERGY DIRECTED TO CFC

RESERVOIR	9.88
BYPASS-SOLAR	.00
BYPASS-BOILER	-.00
TOTAL	9.88

COLD RESERVOIR

GAIN IN ENERGY	1.[illegible]380
LOSS	7.[illegible]785

(ABOVE EXPRESSED IN TERMS OF COLD WATER ENERGY)

SANTA CLARA COMMUNITY CENTER SOLAR HEATING AND COOLING PROJECT

FIGURE 15 MONTHLY TOTALS FOR AUG.

NOTE: ALL QUANTITIES, UNLESS NOTED OTHERWISE, ARE GIVEN IN TERMS OF MILLIONS OF BTUS.

* * * * ENVIRONMENTAL FACTORS * * * *

AVG. AMBIENT TEMP. 67.3 DEGREES F

AVG.WIND SPEED 5.1 M.P.H.

AVG. DAILY INSULATION 2133.8 BTU/DAY SQ.FT.

* * * * COLLECTOR ARRAY CALCULATIONS * * * *

	INCIDENT SOLAR	INCIDENT DURING OPERATION	ENERGY COLLECTED	EFFICIENCY DURING OPERATION	FRACTION OVER DAY	(TF-TA)/QI AVG.
ARRAY #1	279.47	246.19	75.50	30.67	27.02	.7337E+00
ARRAY #2	189.18	166.65	45.94	27.56	24.28	.7316E+00
SYSTEM	468.65	412.85	121.44	29.41	25.91	.7329E+00

* * * * BOILER CALCULATIONS * * * *

GAS USE OF BOILER AS RECORDED BY METER 148931.3 CU.FT. HEAT VALUE OF GAS USED 156.38 MILLION BTUS

ESTIMATED OUTPUT OF BOILER 109.46 MILLION BTUS, BASED ON 70% BOILER EFFICIENCY

* * * * HOT RESERVOIR CALCULATIONS * * * *

ENERGY OUT	6.09	ENERGY CHANGE	-.18	
ENERGY IN		LOSS		
BOILER	.01	MAKE UP WATER	.0000	. GALS.)
SOLAR	20.32	BOIL OFF	.0000	
SOLAR BLEED	.34	INSULATION	14.7492	
SOLAR DUMP	.00			
TOTAL	20.66	TOTAL	14.7492	
PREHEAT TO COLLECTORS	.00			

* * * * ABSORBTION CHILLERS CALCULATIONS * * * *

ENERGY DIRECTED TO CHILLERS

SOLAR	87.21
BOILER	99.62
TOTAL	186.83

C.O.P. OF CHILLERS

SOLAR	.555
BOILER	.520
OVERALL	.536

COLD WATER ENERGY FROM CHILLERS

SOLAR	48.37
BOILER	51.79
TOTAL	100.16

COOLING TOWER ENERGY DISSIPATED 322.67

* * * * HOT FAN COILS, DOMESTIC HOT WATER, COLD FAN COILS, AND COLD RESERVOIR ENERGY CALCULATIONS * * * *

ENERGY DIRECTED TO HFC

SOLAR	.37
BOILER	2.50
HOT RESERVOIR	4.10
CHILLER BLEED	.28
TOTAL	7.25

COLD WATER ENERGY DIRECTED TO CFC

RESERVOIR	101.02
BYPASS-SOLAR	.01
BYPASS-BOILER	-.01
TOTAL	101.02

ENERGY DIRECTED TO DHW SYSTEM (INCLUDES STANDBY LOSSES)

SOLAR	4.6460
BOILER	1.3931
HOT RESERVOIR	.4740
TOTAL	6.5131

HOT WATER USE 2281. GALLONS

COLD RESERVOIR

GAIN IN ENERGY	.8927
LOSS	-1.7559

(ABOVE EXPRESSED IN TERMS OF COLD WATER ENERGY)

* * * * DISTRIBUTIONS OF ENERGY * * * *

PERCENT OF THERMAL ENERGY REQUIREMENT SUPPLIED BY	FOR HEATING	COOLING	DHW	TOTAL
BOILER	40.94	53.32	21.39	51.61
SOLAR	59.06	46.68	78.61	48.39

DISTRIBUTION OF SOLAR ENERGY

	HOT RES.	HFC	HFC-BLEED	CHL	DHW	SUM
PERCENT TO	17.01	.30	.23	71.81	3.83	93.18

DISTRIBUTION OF BOILER ENERGY (BASED ON BOILER/BOILER LOOP OUTPUT AT 70% OVERALL EFFICIENCY)

	HOT RES.	HFC	CHL	DHW	SUM
PERCENT TO	.01	2.29	91.01	1.27	94.57

DISTRIBUTION OF HOT RESERVOIR ENERGY

	HFC	DHW	PREHEAT	SUM
PERCENT TO	67.33	7.78	.00	75.11

* * * * TOTAL ENERGY LOADS * * * *

WATER SIDE HEATING LOAD	7.25	
CFC LOAD	101.02	
DHW LOAD	6.51	
SOLAR ENERGY UTILIZED BY SYSTEM	97.08	(AFTER HOT TANK LOSS)
BOILER ENERGY UTILIZED BY SYSTEM	103.52	
OPERATING ELECTRICAL ENERGY	52.07	15257.3 KWH (FOR OPERATION OF HEATING/COOLING SYSTEM)
TOTAL ENERGY CONSUMED	305.53	(ALL ENERGY INPUT TO HEATING/COOLING SYSTEM)
SOLAR FRACTION OF BUILDING LOAD	.443	(SOLAR FRACTION OF FAN COIL LOADS)
SYSTEM PERFORMANCE FACTOR	.348	(THIS FACTOR IS THE RATIO OF THE TOTAL ENERGY DELIVERED TO THE BUILDING LOAD TO THE TOTAL EQUIVALENT FOSSIL FUEL ENERGY EXPENDED. THIS TAKES INTO ACCOUNT THE FOSSIL FUEL USED TO GENERATE ELECTRICAL ENERGY USED.)

SANTA CLARA COMMUNITY CENTER SOLAR HEATING AND COOLING PROJECT

FIGURE 16 SIX MONTH TOTAL, APRIL-SEPTEMBER

NOTE: ALL QUANTITIES, UNLESS NOTED OTHERWISE, ARE GIVEN IN TERMS OF MILLIONS OF BTUS.

* * * * ENVIRONMENTAL FACTORS * * * *

AVG. AMBIENT TEMP. 63.6 DEGREES F

AVG.WIND SPEED 3.4 M.P.H.

AVG. DAILY INSOLATION 2170.3 BTU/DAY SQ.FT.

* * * * COLLECTOR ARRAY CALCULATIONS * * * *

	INCIDENT SOLAR	INCIDENT DURING OPERATION	ENERGY COLLECTED	EFFICIENCY DURING OPERATION	FRACTION OVER DAY	(TF-TA)/QI AVG.
ARRAY #1	1678.02	1445.87	445.36	30.80	26.54	.7370E+00
ARRAY #2	1135.89	978.74	270.64	27.65	23.83	.7286E+00
SYSTEM	2813.90	2424.62	703.58	29.02	25.00	.7336E+00

* * * * BOILER CALCULATIONS * * * *

GAS USE OF BOILER AS RECORDED BY METER 492455.4 CU.FT. HEAT VALUE OF GAS USED 517.08 MILLION BTUS

ESTIMATED OUTPUT OF BOILER 361.95 MILLION BTUS, BASED ON 70% BOILER EFFICIENCY

* * * * HOT RESERVOIR CALCULATIONS * * * *

ENERGY OUT	118.58
ENERGY IN	
BOILER	-.01
SOLAR	168.81
SOLAR BLEED	6.53
SOLAR DUMP	.23
TOTAL	175.57
PREHEAT TO COLLECTORS	.00

ENERGY CHANGE	-1.74	
LOSS		
MAKE UP WATER	.0000	(. GALS.)
BOIL OFF	.0000	
INSULATION	58.7294	
TOTAL	58.7294	

**** ABSORBTION CHILLERS CALCULATIONS ****

ENERGY DIRECTED TO CHILLERS

SOLAR	430.79
BOILER	286.64
TOTAL	717.42

C.O.P. OF CHILLERS

SOLAR	.557
BOILER	.522
OVERALL	.543

COLD WATER ENERGY FROM CHILLERS

SOLAR	239.93
BOILER	149.72
TOTAL	389.65

COOLING TOWER ENERGY DISSIPATED 1216.26

**** HOT FAN COILS, DOMESTIC HOT WATER, COLD FAN COILS, AND COLD RESERVOIR ENERGY CALCULATIONS ****

ENERGY DIRECTED TO HFC

SOLAR	28.03
BOILER	38.48
HOT RESERVOIR	92.23
CHILLER BLEED	4.57
TOTAL	163.31

ENERGY DIRECTED TO DHW SYSTEM (INCLUDES STANDBY LOSSES)

SOLAR	27.3175
BOILER	5.7174
HOT RESERVOIR	5.8692
TOTAL	38.9041

HOT WATER USE 14203. GALLONS

COLD WATER ENERGY DIRECTED TO CFC

RESERVOIR	379.11
BYPASS-SOLAR	.04
BYPASS-BOILER	-.04
TOTAL	379.12

COLD RESERVOIR

GAIN IN ENERGY	1.3912
LOSS	9.1457

(ABOVE EXPRESSED IN TERMS OF COLD WATER ENERGY)

* * * * DISTRIBUTIONS OF ENERGY * * * *

PERCENT OF THERMAL ENERGY REQUIREMENT SUPPLIED BY	FOR HEATING	FOR COOLING	FOR DHW	FOR TOTAL
BOILER	23.44	39.95	14.70	35.97
SOLAR	76.56	60.05	85.30	64.03

DISTRIBUTION OF SOLAR ENERGY

	HOT RES.	HFC	HFC-BLEED	CHL	DHW	SUM
PERCENT TO	24.95	3.98	.65	61.23	3.88	94.70

DISTRIBUTION OF BOILER ENERGY (BASED ON BOILER/BOILER LOOP OUTPUT AT 70% OVERALL EFFICIENCY)

	HOT RES.	HFC	CHL	DHW	SUM
PERCENT TO	-.00	10.63	79.19	1.58	91.40

DISTRIBUTION OF HOT RESERVOIR ENERGY

	HFC	DHW	PREHEAT	SUM
PERCENT TO	77.78	4.95	.00	82.73

* * * * TOTAL ENERGY LOADS * * * *

WATER SIDE HEATING LOAD	163.31	
CFC LOAD	379.12	
DHW LOAD	38.90	
SOLAR ENERGY UTILIZED BY SYSTEM	588.81	(AFTER HOT TANK LOSS)
BOILER ENERGY UTILIZED BY SYSTEM	330.83	
OPERATING ELECTRICAL ENERGY	283.60	83094.9 KWH (FOR OPERATION OF HEATING/COOLING SYSTEM)
TOTAL ENERGY CONSUMED	1389.48	(ALL ENERGY INPUT TO HEATING/COOLING SYSTEM)
SOLAR FRACTION OF BUILDING LOAD	.572	(SOLAR FRACTION OF FAN COIL LOADS)
SYSTEM PERFORMANCE FACTOR	.398	(THIS FACTOR IS THE RATIO OF THE TOTAL ENERGY DELIVERED TO THE BUILDING LOAD TO THE TOTAL EQUIVALENT FOSSIL FUEL ENERGY EXPENDED. THIS TAKES INTO ACCOUNT THE FOSSIL FUEL USED TO GENERATE ELECTRICAL ENERGY USED.)

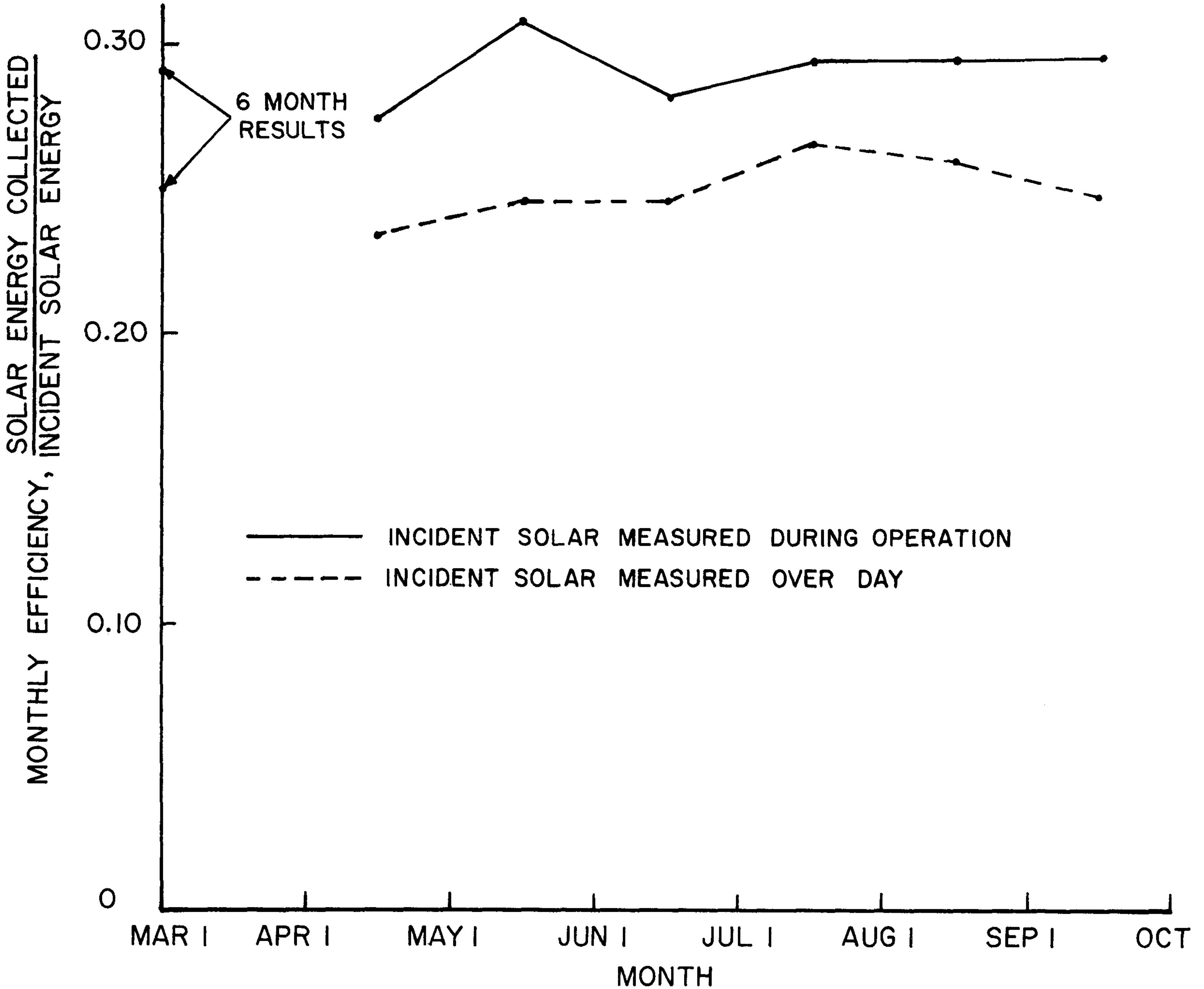


FIGURE 17 - MONTHLY EFFICIENCY OF COLLECTOR ARRAYS

The results for May, August and the entire six months are:

Period	ϵ
May	0.13
August	0.19
Six Months	0.15

The accuracy of the energy balances on the chillers and on the collector loop is affected both by errors in the measured flow rates and by errors in the water temperature measurements.

6.4 PERFORMANCE OF INDIVIDUAL SYSTEM COMPONENTS

This section presents data on the thermal performance of the collectors, chillers and mechanical components for the six month period from April to September 1977.

6.4.1 Solar Collector Performance

Figure 18 presents measured instantaneous collector efficiencies for the two solar collector arrays. Instantaneous performance is based on data obtained within 45 minutes of solar noon. The overall collector/piping system shows significant thermal capacity effects when output temperatures are rising or falling. Therefore, measured instantaneous values of collector efficiency are used only if they are obtained when the output temperature is near the maximum for that day. The only state points available which meet the constraints above during the summer months were those obtained during operation of both chillers. As a result, each point was taken in the range of collector outlet temperatures from 200°F - 230°F. Consequently, measured instantaneous values of collector efficiency are available only in a small range of fluid parameter values. The spread of efficiency values shown is indicative of the difficulty in achieving steady state points in an operating system.

All efficiencies are based on the original aperture area of the collectors, 16.25 ft^2 per collector.* Resealing of the gaskets reduced the aperture area to 15.87 $ft.^2$. Also shown in Figure 18 are the test results obtained by Lockheed at their Palo Alto Research Laboratory on the collector prototype.

Overall, the collectors have demonstrated reasonable performance. However, the values of instantaneous collector efficiency measured during system operation are somewhat lower than the values obtained by Lockheed on the prototype collectors. Several factors may account

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*The outside area of the collector boxes is 17.84 $ft.^2$.

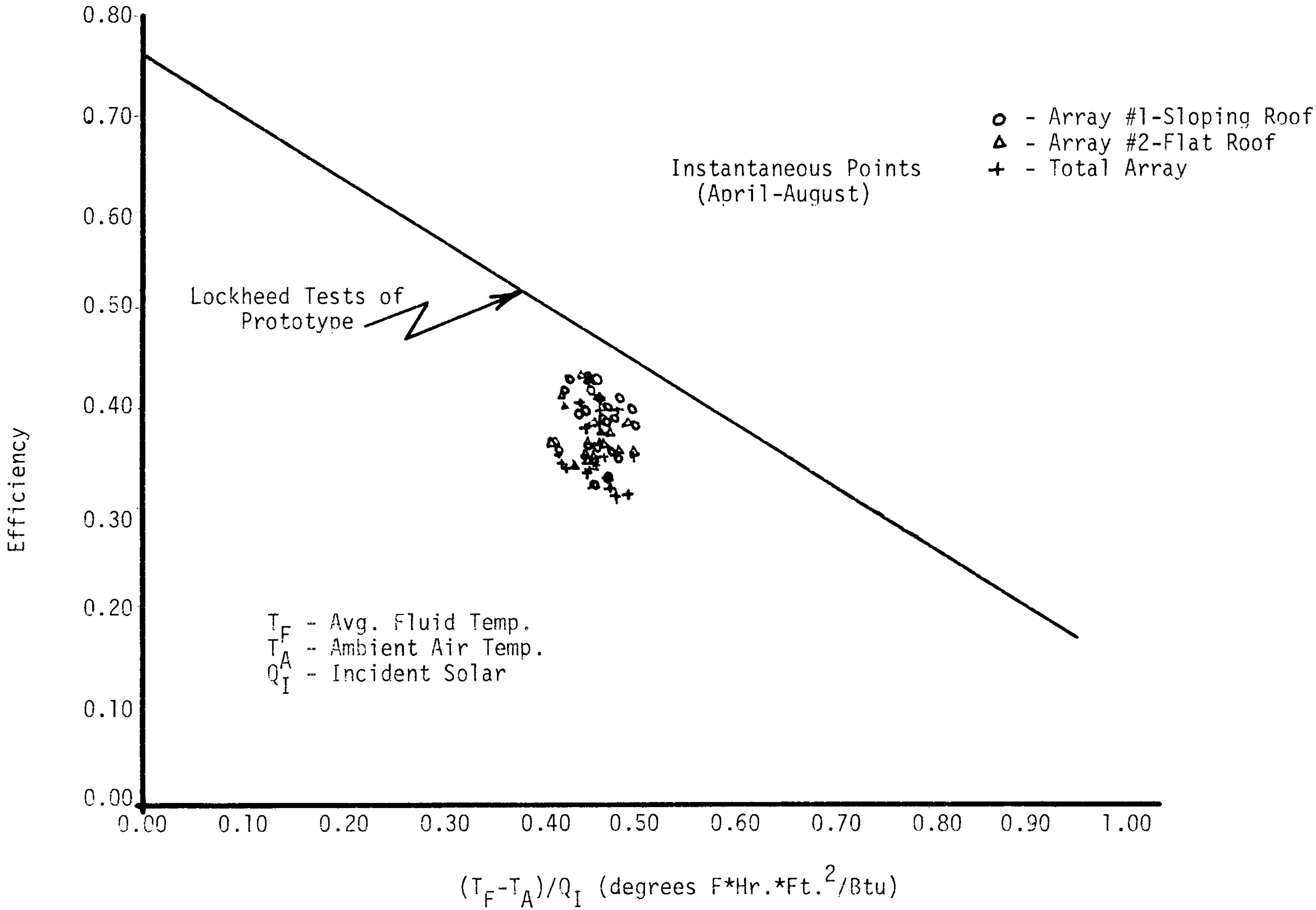


Figure 18.- Collector Array Performance for Santa Clara Community Center for April-Sept., 1977

for the discrepancies. First, the system collectors are not cleaned regularly because the resulting increase in performance (2-3%) does not offset the labor cost of cleaning. Second, measurements of the flow distribution across the collector arrays indicate that it is not perfectly uniform. Therefore, some of the collectors operate at higher temperatures than others.

The data shown in Figures 14-16 and 18 show higher efficiencies for Array #1 than Array #2. The primary cause of the discrepancy appears to be higher ambient temperatures near Array #1. Because Array #1 lies flat on a steel roof and Array #2 sits on wooden racks above a flat gravel roof, the ambient temperatures can be up to 40°F higher near Array #1. This is not taken into account in the fluid parameter as there is only one ambient temperature sensor and it is located beneath Array #2.

6.4.2 Absorption Chiller Performance

Operating data for the absorption chillers is given in Figures 19 and 20. Figure 19 presents the measured Cooling Capacity Fraction (CCF) as a function of inlet temperature. The CCF is defined to be the instantaneous cooling output of the chillers divided by 50 tons, the rated capacity of the two units. Figure 20 gives the measured Coefficient of Performance versus inlet temperature. The COP is defined here to be the instantaneous cooling output divided by the instantaneous firing water energy input.

The values shown in Figures 19 and 20 are for both chillers operating in parallel in either solar or boiler fired modes. Values are given for two different flow rates due to the rebalancing of the firing water and chilled water inputs to the chillers. This was done in early August when flow measurement work revealed imbalances and the flow rate to each chiller was adjusted to meet the manufacturer's specifications.

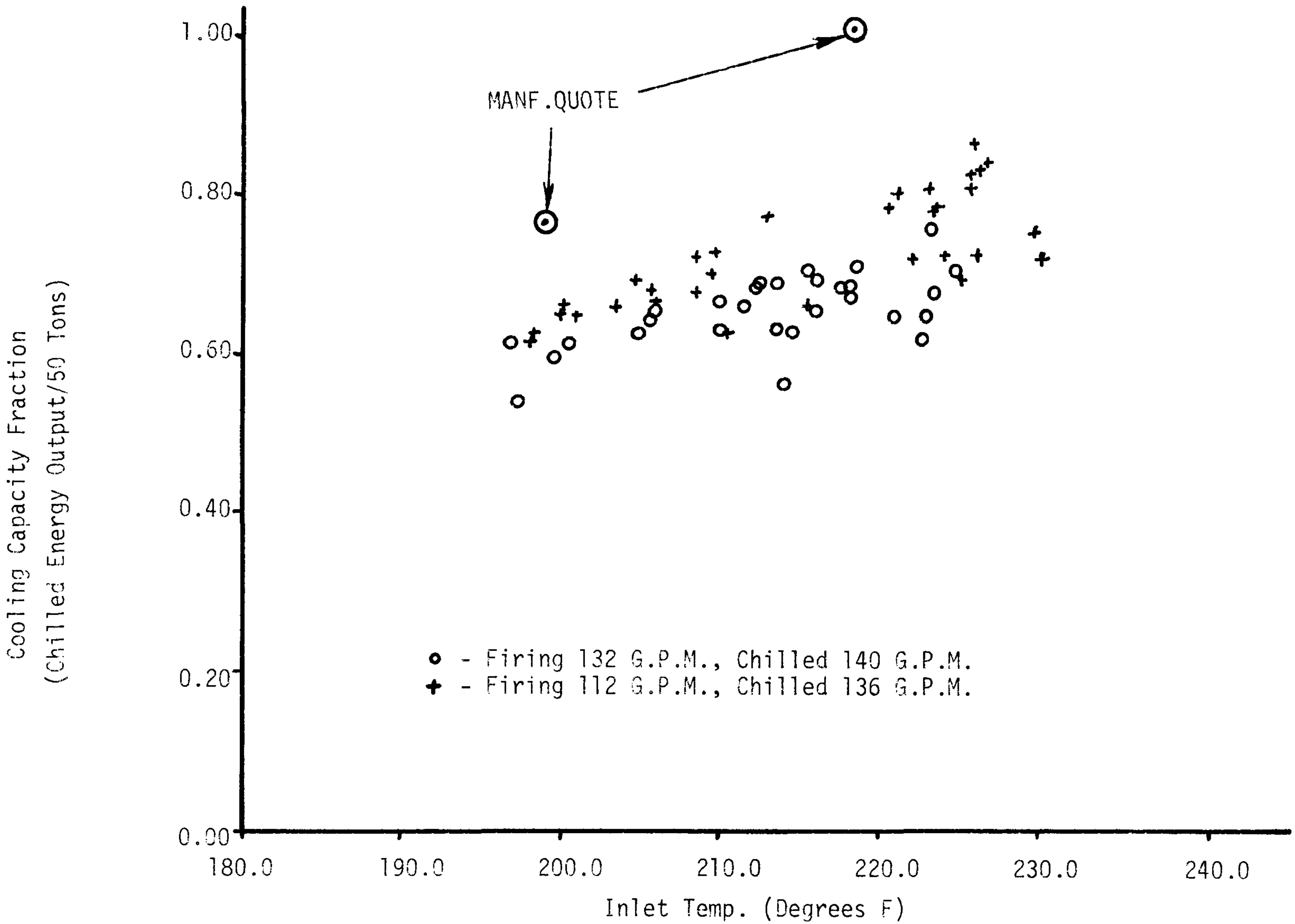


Figure 19.- Measured Instantaneous Cooling Capacity Fraction for Absorption Chillers During April - September, 1977

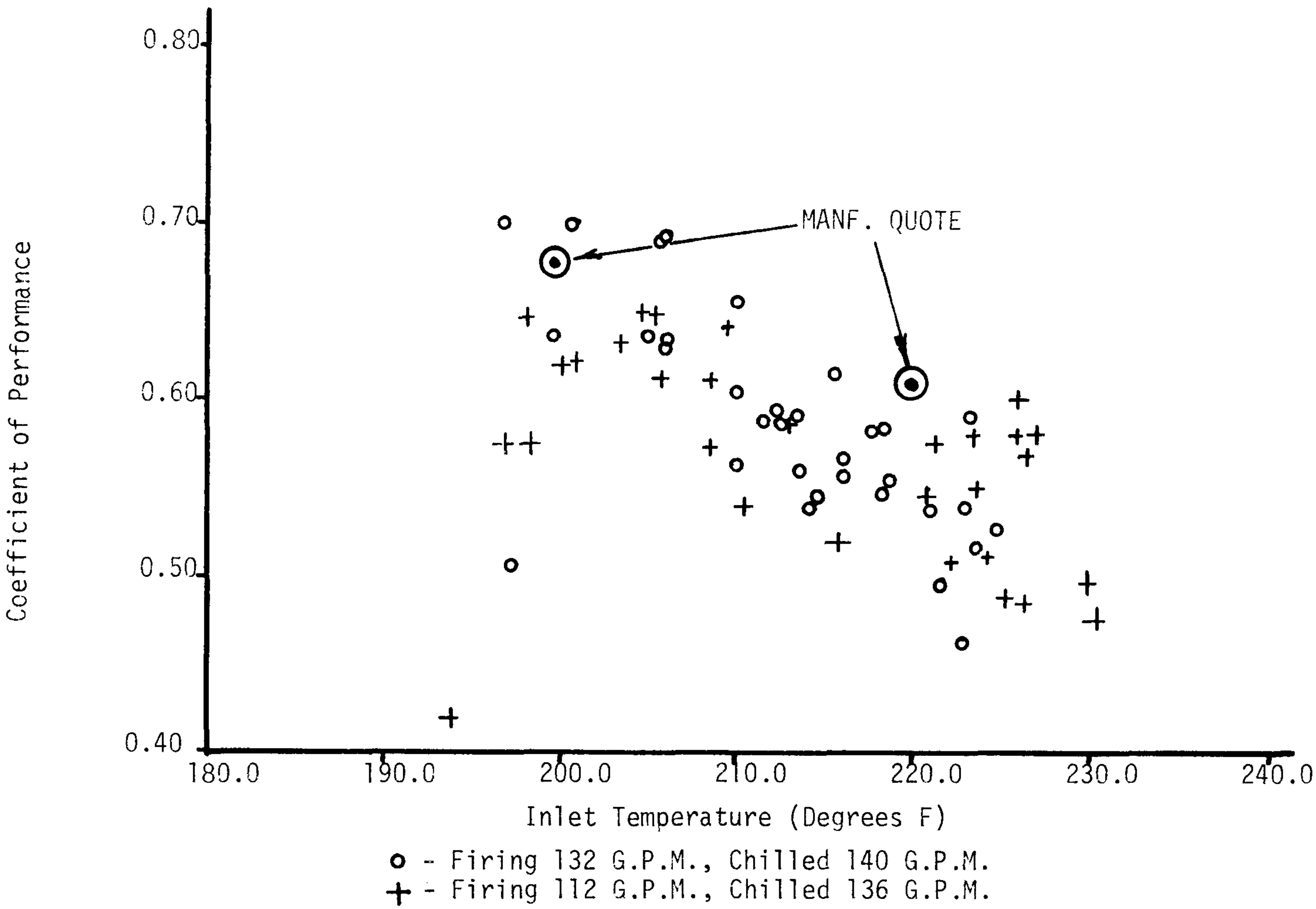


Figure 20. - Measured Instantaneous Coefficient of Performance for Absorption Chillers During April - September, 1977

Condensing water inlet temperatures were in the range of 76-80°F for all values shown. Chilled water inlet values were in the range of 53-58°F. The CCF and COP values quoted by the manufacturer and shown in Figures 19 and 20 are based on an 80°F condensing water inlet temperature and a 55°F chilled water inlet temperature.

While the measured COP values are close to those quoted by the manufacturer, the chiller capacities are approximately 20 percent lower. The effect of this impaired capacity on the system is to force the chillers to run longer with slightly higher net energy requirements than rated. As a result the chillers run at higher temperatures during collector operation than would normally be the case causing the collectors to operate less efficiently.

Possible causes for this decrease in performance are lack of proper vacuum in the units or low solution concentration. Also, there has been evidence of scale in the cooling tower and condensor water line which would lower the performance of the condensor loop.

6.4.3 Performance of the Boiler, Thermal Reservoir and Control System

The gas fired boiler included in the system is rated at an efficiency of 80% by the manufacturer. The boiler loop consists of the boiler, a short loop of piping and a pump.

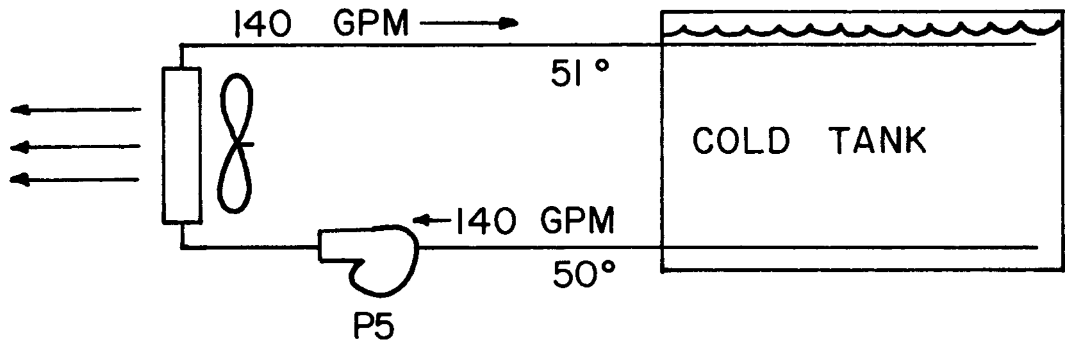
The thermal efficiency of the boiler loop can be calculated by summing the energy actually supplied by the boiler and dividing it by the heating value of the gas required by the boiler. Line losses are fairly constant since the temperature of the boiler stays within the range of 195-210°F. Hence, the loop efficiency decreases as the load on the boiler decreases. The loop efficiency was found to be 53% at a load equal to 1/3 of the boiler capacity and 71% at close to full load. Full boiler load conditions are present only during the summer months when the chiller demand for boiler energy is high.

Accurate measurements of tank losses in the hot and cold storage tanks (thermal reservoirs) are difficult to obtain in an operating system because the measured energy flows into and out of the tanks are often considerably larger than the losses, particularly for the cold tank. Consequently, the magnitude of the losses approaches that of the errors in measurement of the energy flows. Performance calculations did indicate an unexpectedly high loss from the hot storage tank when the system was first started up. Most of the loss appeared to be due to convection through the pressure-relief stack. A hinged cap and a restriction have been added to the stack and have successfully reduced the losses.

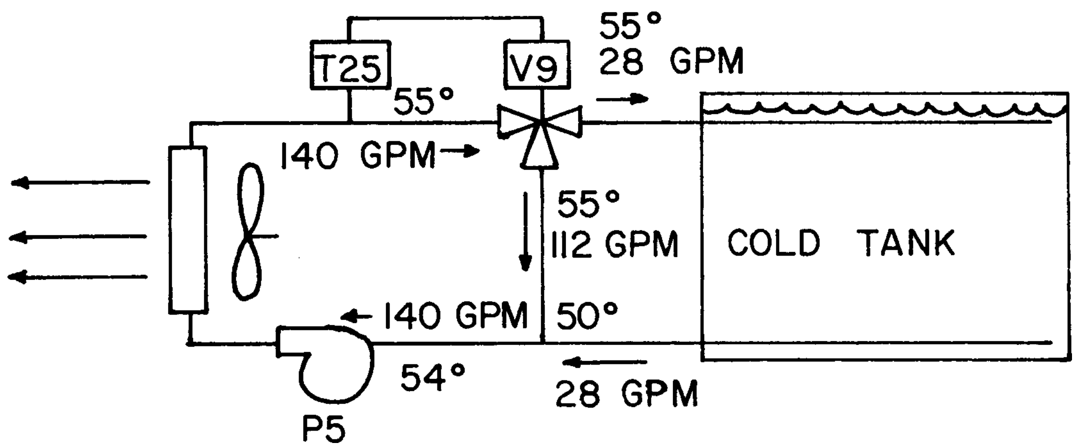
Stratification of the cold tank has been successful as indicated by the data from the nine temperature sensors located in the tank. Initially, however, stratification within the tank was being destroyed by the external action of the CFC loop. This occurred under low cooling load conditions when the CFC loop returned the flow to the top of the tank at close to the bottom temperature (see sketch 1 below.) The problem was solved by the installation of a temperature modulating valve in the CFC loop in early June 1977. The valve maintains the output temperature of the CFC loop at 55° by recirculating some of the flow (see sketch 2 below.) The redesign has successfully prevented destratification of the tank during partial load conditions.

Data obtained during the cooling season indicate that only 20% of the energy required for the DHW system goes to heating make-up water. The remaining 80% is used to make up for standby losses in the system. This high percentage is due to the low demand for hot water, approximately 80 gallons a day, and the large size of the hot water circulation system.

Management of the system temperatures by the control system has been an important factor in the thermal performance of the overall system. The control system appears to be functioning well since the system and major system components are operating near planned performance conditions.



SKETCH 1. PARTIAL LOAD CONDITION BEFORE INSTALLATION OF CFC MODULATING VALVE



SKETCH 2. PARTIAL LOAD CONDITION AFTER INSTALLATION OF CFC MODULATING VALVE

6.5 Comparison of Energy Used by Present Solar System and Estimated Energy Requirements of Two Non-Solar Systems.

It is useful to compare the performance of the present system (system 1) with equivalent nonsolar systems in terms of auxiliary (gas and electric) energy requirements. We have selected two systems for comparison. System 2 is the heating and cooling system originally chosen for the building before the switch to a solar design was made. The original design consisted of an electric vapor compression refrigeration unit with a capacity of 61.7 tons. It is assumed to have an overall COP of 3.0. A gas fired boiler with an estimated overall loop efficiency of 70% was originally selected for space heating. Domestic hot water (DHW) would have been provided by a gas fired heater with an assumed efficiency of 70%. The original design also included a two horsepower Hot Fan Coil pump, a two horsepower Cold Fan Coil pump, a 1.5 horsepower condenser water pump and an eight horsepower motor for the cooling tower fan.

For comparison purposes, a second alternative (non-solar) system (system 3) was considered. This system would consist of the equipment in the present solar system except for the solar collectors and the hot storage reservoir and their associated pumps. In this system all thermal energy would come from the boiler.

Auxiliary electric energy use of the solar energy system (system 1) is equal to the sum of the energy used by all the pumps in the system, the cooling tower fan, and other small energy drains such as the control system and the chillers. The data system records the length of time of operation of these devices and, based on direct measurement of each device's electric power use, the total energy use is calculated.

Electric energy use of the vapor compression system (system 2) for cooling is estimated by dividing the cooling energy provided to the building by the assumed COP for the unit. The auxiliary electric energy use value is estimated using data on duration of operation of the pumps in the existing system which would be required for system 2.

For the boiler fired absorption cooling system (system 3), auxiliary energy use is based on that for the existing solar system, minus the energy use of those pumps not required. A detailed description of the analysis used to estimate the energy requirements of systems 2 and 3 is given in Appendix C.

Table II compares the measured auxiliary energy requirements for the present solar system (system 1) and the two alternative nonsolar systems (systems 2 and 3) for the six month period, April-September 1977 and for the months of May and August. The values in Table II do not include the electrical requirements for lights, office equipment, etc.

For comparisons of total non-solar energy requirements, we have assumed that the electrical energy used is generated at a thermal efficiency of 35 %. The average daily auxiliary electrical energy requirements for all three systems are given in Figure 21. Note that the electrical energy used by the vapor compression system for cooling is not included in the auxiliary electrical energy requirement.

TABLE II. FOSSIL ENERGY REQUIREMENTS FOR SOLAR AND NON-SOLAR SYSTEMS*
(a) May 1977

	SYSTEM 1 Present Solar System	SYSTEM 2 Electric Driven Cooling	SYSTEM 3 Boiler Fired Absorption Cooling
Gas Energy Used for			
Heating	42	124	124
Cooling	0	0	71
DHW	2	12	12
TOTAL	44	136	207
Electrical Energy Used for			
Cooling	0	3	0
Auxiliary	17	5	10
Air Handler	25	25	25
TOTAL	42	33	36
TOTAL FOSSIL ENERGY REQUIREMENTS**	164	230	310

* Unless otherwise noted all quantities are reported in millions of BTU's.

** An electric generating plant efficiency of 35% is assumed.

TABLE II. FOSSIL ENERGY REQUIREMENTS FOR SOLAR AND NON-SOLAR SYSTEMS*
(b) August 1977

	SYSTEM 1 Present Solar System	SYSTEM 2 Electric Driven Cooling	SYSTEM 3 Boiler Fired Absorption Cooling
Gas Energy Used for			
Heating	4	11	11
Cooling	150	0	282
DHW	2	10	10
TOTAL	156	21	303
Electrical Energy Used for			
Cooling	0	34	0
Auxiliary	26	6	22
Air Handler	26	26	26
TOTAL	52	66	48
TOTAL FOSSIL ENERGY REQUIREMENTS**	305	210	440

* Unless otherwise noted all quantities are reported in millions of BTU's.

** An electric generating plant efficiency of 35% is assumed.

TABLE II. FOSSIL ENERGY REQUIREMENTS FOR SOLAR AND NON-SOLAR SYSTEMS*
(c) April - September 1977

	SYSTEM 1 Present Solar System	SYSTEM 2 Electric Driven Cooling	SYSTEM 3 Boiler Fired Absorption Cooling
Gas Energy Used for			
Heating	60	284	284
Cooling	448	0	1106
DHW	9	64	64
TOTAL	517	348	2454
Electrical Energy Used for			
Cooling	0	126	0
Auxiliary	133	33	104
Air Handler	151	151	151
TOTAL	284	310	255
TOTAL FOSSIL ENERGY REQUIREMENTS**	1328	1234	2183

* Unless otherwise noted all quantities are reported in millions of BTU's.

** An electric generating plant efficiency of 35% is assumed.

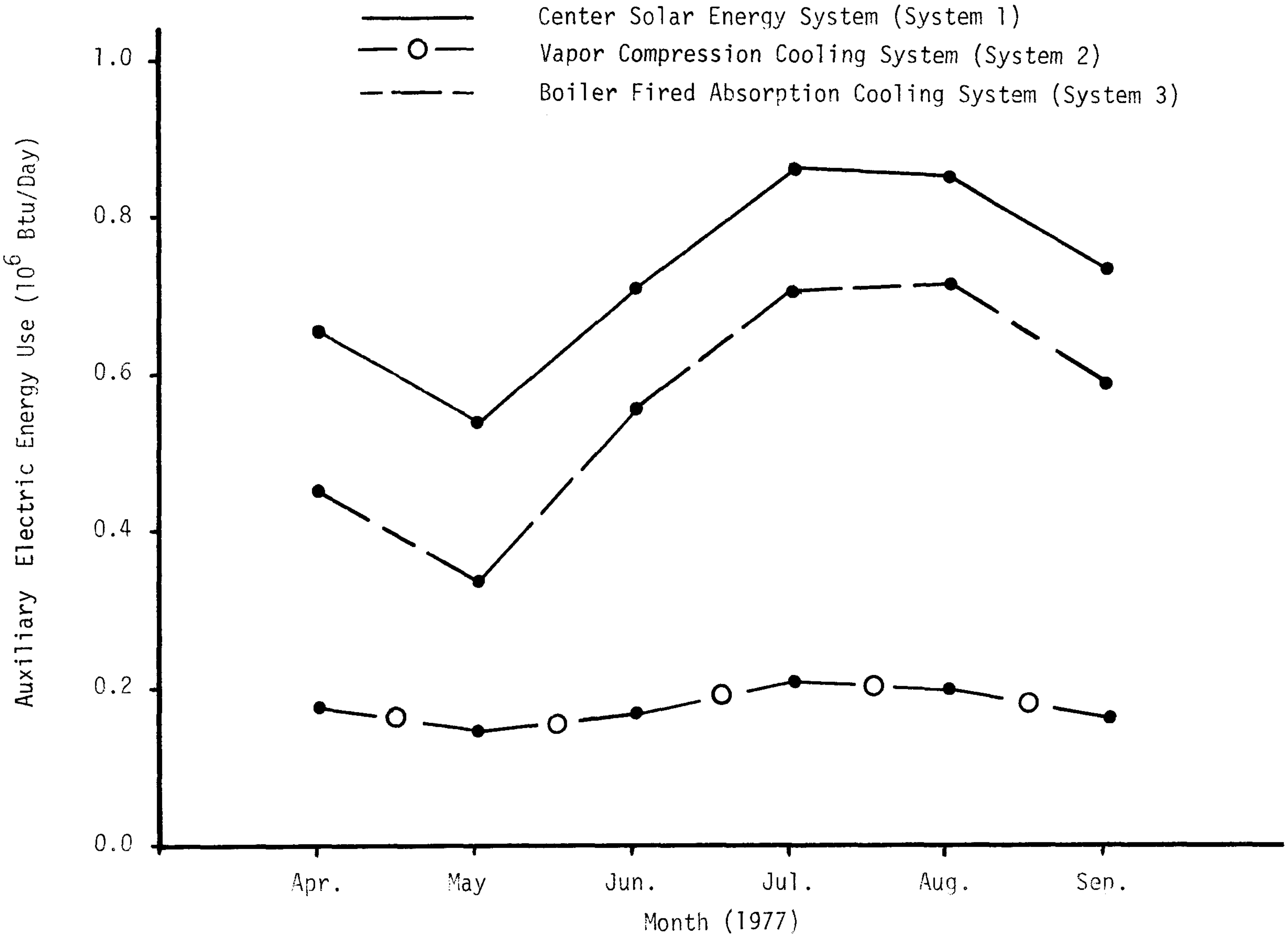


Figure 21. Auxiliary Electric Energy Use for Present Solar Energy System and Two Alternate Non-Solar Systems

Section 7

DISCUSSION OF FIRST SIX MONTHS OF DATA ACQUISITION, CURRENT PROBLEMS AND PLANS FOR FUTURE WORK

7.1 DISCUSSION

The first six months of data acquisition for the Santa Clara Community Recreation Center solar heating and cooling system have verified the design philosophy adopted by Lockheed. Although the measured performance of the collectors and chillers is slightly lower than expected, the system has demonstrated its stability and efficiency in collecting solar energy at high temperatures for driving the water chillers and has provided a significant percentage of thermal energy required to heat and cool the building (see Fig. 11). The basic concept of using high performance flat plate solar collectors to drive solar absorption chillers has been verified.

However, the performance calculations (see Table II) show a large auxiliary energy requirement for the system, both for natural gas and for electricity. As Table II shows for the six month cooling season, the solar energy system required more fossil fuel energy, in natural gas and fuel at the electric generating plant, than a conventional system would have.

Significant natural gas demand was predicted by the system simulation performed by Lockheed and the actual use of natural gas closely follows the predicted values.[1] Such a large natural gas use results from the relative size of the collector/chiller system capacity and the building cooling load. Additionally, burning natural gas to provide thermal energy for an absorption chiller to produce cooling has an inherent low efficiency. The boiler operates at an average efficiency of 70% and the rated COP of the chillers is 0.67. The combined result gives a net COP of 0.47.

It was expected that the increase in natural gas use would be somewhat offset by a decrease in electric energy use. However, two factors worked against this offset. First, electric driven vapor compression cooling has an

[1] See Figure 12

inherently higher coefficient of performance. Assuming a generating plant burns natural gas to produce electric energy at an efficiency of 35% and the vapor compression chiller operates at a COP of 3.0, the net COP is 1.15. This is 2.5 times more efficient than gas fired absorption cooling. Secondly, the electric energy requirements of the many pumps in the solar energy system were found to be significant. Figure 21 shows that much of this electric energy was not required to collect the solar energy, but was required to drive the pumps necessary for the absorption chiller fluid loops.

The period of system performance covered in this progress report is for the cooling-dominated summer months of April--September. The measured performance of this system shows that careful attention must be shown during system design to natural gas and electric energy use.

First, the requirement for burning natural gas for driving the absorption cooling units must be reduced as much as possible. This could be accomplished by increasing the collector area, improving chiller efficiency or reducing building cooling load. However, most realistic solar energy systems could not provide 100% of the cooling load. Due to the inherent low efficiency of gas fired absorption cooling, the energy penalty of providing even a small percentage of the cooling load may be unacceptable. This may make boiler-fired auxiliary cooling an untenable alternative.

Section 3 of Appendix C describes a calculation of the auxiliary energy use of such a solar-driven absorption chiller system with vapor compression chiller backup. This calculation shows that this system would have a net savings in fossil fuel used.

The second area in which design attention is required is in reduction of electrical energy use for pumping. It may be possible to accomplish this by more efficient piping design or more careful pump selection.

The data acquisition system (DAS) has performed well. Its versatility and computational power have made it possible to accurately measure the performance of the overall system and its components in sufficient detail to locate the sources of performance degradation. Another important feature of the present DAS is its ability to assist in the modeling of the system. Improvement of this system depends upon a good simulation model. The model in turn requires accurate measurement of the performance of the important system components. The Hewlett-Packard DAS is especially useful in this respect because of its ability to get data over short time periods and to sense when each component is operating (event sense capability).

7.2 CURRENT PROBLEMS

At present there are still some areas in which the data acquisition system is not functioning satisfactorily:

1. A major difficulty is the measurement of energy used for heating and cooling through the use of sensors placed in the air duct system for each zone. The initial energy calculations with these sensors proved to be quite different from the energy flows measured in the fluid loops for the fan coil units. The large velocity and temperature gradients encountered across these ducts often result in inaccurate measurement of energy flows when a single sensor is used.

2. The drift in calibration of the bridge circuits of some of the data sensors is a continuing problem. At present this is being dealt with by constant recalibration of the drifting circuits but a more lasting cure for this problem is being sought.

7.3 FUTURE WORK

Work will continue on the current contract for the next six months in preparation for the one-year performance report. Activities which will tentatively take place during this time period include:

1. A detailed study of the collector array temperature distributions as an indication of flow characteristics. This information may provide an explanation for measured collector efficiencies being somewhat lower than expected.

2. Further development of the computer modeling program. This program is in its final stages of development with the major remaining work being a "tuning" process of adjusting parameters to align the model response with that of the system.

3. An investigation of control system setpoint optimization, primarily through use of the computer modeling program.

4. An effort to define ambient air temperature sensor locations for the measurement of collector array performance. Currently only one ambient air temperature sensor is being used. It is possible that it does not give representative readings for both collector arrays.

5. An investigation into the causes of the high electrical usage. It is possible that pump operation is inefficient because of improper sizing or excessive throttling.

6. A study of the effects of thermal capacity in the collector loop on the performance calculations.

7. Detailed information on the accuracies of measured flow rates and temperatures will be obtained so that accurate information will be available for component characterization.

8. Based on the experience gained during the first year of solar operation, recommendation for future design improvements will be made.

All of the above tasks are aimed ultimately at defining and improving the performance of the present system through the data acquisition system and the computer simulation model. An equally important task that will be carried out during this period is a study of the system performance when it is primarily operating in the heating mode.

REFERENCES

1. "Santa Clara, California, Community Center Commercial Solar Demonstration Design and Construction Report, by the Lockheed Palo Alto Research Laboratory, NTIS Report No. SAN/1083-77/1, September 1977.

2. Lawrence B. Anderson, "Experiences from the Santa Clara Community Center Solar Energy Project," Proceedings of the 1977 Flat Plate Solar Collector Conference, Feb. 28 - Mar 2, 1977, Orlando, FL, Florida Solar Energy Center Report, FSEC-77-8, September 1977.

APPENDIX A

LIST OF PERFORMANCE CALCULATIONS MADE IN REAL TIME

NO.	CALCULATION (*indicates an estimate)
1	Incident solar energy during collector operation--collector array #1.
2	Incident solar energy during collector operation--collector array #2.
3	Collected solar energy--collector array #1 ΔT.
4	Collected solar energy--collector array #2 ΔT.
5	Collected solar energy--total collector array ΔT.
6	Instantaneous efficiency---collector array #1
7	Instantaneous efficiency--collector array #2
8	Instantaneous efficiency--total collector array
9	Daily efficiency--collector array #1
10	Daily efficiency--collector array #2
11	Daily efficiency--total collector array
16*	Boiler energy output--based on 70% efficiency
17	Firing energy consumed during operation of one chiller from solar
18	Firing energy consumed during operation of one chiller from boiler
19	Firing energy consumed during all operations of chillers
20	Cold water energy from chillers using solar
21	Cold water energy from chillers using boiler
22	Cold water energy from chillers--total
23	Energy dissipated by cooling tower
24	COP of chillers
25	Energy input to heat exchanger from hot tank
26	Energy input to hot tank from boiler
27	Energy input to hot tank from solar during low solar mode

28 Energy to hot fan coils--from solar
29 Energy to hot fan coils--from boiler
30 Energy to hot fan coils--from solar heated chiller firing water
31 Energy to hot fan coils--from hot tank
32 Energy to hot fan coils--total
33 Energy to cold fan coils--from cold tank
34 Energy to cold fan coils--tank bypass, chillers run by solar
35 Energy to cold fan coils--tank bypass, chillers run by boiler
36 Energy to cold fan coils--total
37 Hot tank energy level
38 Energy used to heat hot tank make-up water
39* Energy lost to boil off from hot tank
40 Energy consumed heating domestic hot water--from boiler
41 Energy consumed heating domestic hot water--from solar
42 Energy consumed heating domestic hot water--total
43 Heating energy supplied to zone 1
44 Heating energy supplied to zone 2
45 Heating energy supplied to zone 3
46 Heating energy supplied to zone 4
47 Heating energy supplied to zone 5a
48 Heating energy supplied to zone 5b
49 Heating energy supplied to zone 5c
50 Heating energy supplied to zone 6
51 Heating energy supplied to zone 7
52 Heating energy supplied to zone 8
53 Heating energy supplied to zone 9
54 Heating energy supplied to zone 10
55 Cooling energy supplied to zone 1
56 Cooling energy supplied to zone 2
57 Cooling energy supplied to zone 3
58 Cooling energy supplied to zone 4
59 Cooling energy supplied to zone 5
60 Cooling energy supplied to zone 6
61 Cooling energy supplied to zone 7

62 Cooling energy supplied to zone 8
63 Cooling energy supplied to zone 9
64 Cooling energy supplied to zone 10
65 Cooling energy supplied by economizer to zone 1
66 Cooling energy supplied by economizer to zone 2
67 Cooling energy supplied by economizer to zone 3
68 Cooling energy supplied by economizer to zone 4
69 Cooling energy supplied by economizer to zone 5
70 Cooling energy supplied by economizer to zone 6
71 Cooling energy supplied by economizer to zone 7
72 Cooling energy supplied by economizer to zone 8
73 Cooling energy supplied by economizer to zone 9
74 Cooling energy supplied by economizer to zone 10

80 Energy consumed in operation of two chillers--from solar
81 Energy consumed in operation of two chillers--from boiler
82 Energy input to hot tank during dump

87 Total incident solar energy--collector array #1
88 Total incident solar energy--collector array #2
89 Total incident solar energy--total collector array
90 Energy input to hot tank during bleed
91* Energy input to heat exchanger from solar during low solar mode
92* Energy input to heat exchanger from boiler
93* Energy input to heat exchanger from dump and bleed
94* Energy output of heat exchanger to building from energy in tank

96 Total heating energy delivered to zones
97 Total cooling energy delivered to zones
98 Total cooling energy delivered by the economizer to zones
99 Energy used to preheat collectors
100 Energy consumed heating domestic hot water--from hot tank
102 Electrical energy consumed by chiller 1
103 Electrical energy consumed by chiller 2
104 Electrical energy consumed by control system and boiler draft fan

115 Electrical energy consumed by pump 1
116 Electrical energy consumed by pump 2
117 Electrical energy consumed by pump 2A
118 Electrical energy consumed by pump 3
119 Electrical energy consumed by pump 4
120 Electrical energy consumed by pump 5
121 Electrical energy consumed by pump 6
122 Electrical energy consumed by pump 7
123 Electrical energy consumed by pump 8
124 Electrical energy consumed by pump 9
125 Electrical energy consumed by pump 10
126 Electrical energy consumed by air handlers
127 Total electric energy use
128 Total use of solar energy
129 Total use of boiler energy
130 Total energy use
131 Total energy input to heating/cooling system (solar, fossil fuel, electricity)
132 Fluid parameter, (TF-TA)/QI-collector array #1
133 Fluid parameter, (TF-TA)/QI-collector array #2

148 Daily average of average building interior temperature
149 Daily average ambient temperature
150 Daily average wind speed

Time Length Calculations

As a result of the manner in which the real time calculatins are made, time lengths associated with each computation are summed over the day. The locations in the time lengths array correspond numerically to those in the real time calculations array and provide information on how long the solar energy system operated in each of the various sub-modes. For example, location 31 in the time length array contains the period over which the system supplied energy to the hot fan coils from the hot tank.

Additionally, the following items are stored within the time length array:

- Boiler gas use meter output
- Hot tank make-up water meter output
- Domestic hot water use meter output

APPENDIX B

COMPUTER OUTPUT OF PERFORMANCE DATA

This appendix defines some of the terms included in the computer listing of performance data given in the test. Many of the terms shown are covered in detail in Section 6 of the report.

Environmental Factors

The averages of ambient temperature and wind speed are taken over the entire day. The average insolation value is also over the entire day and is recorded in the plane of the collectors.

Collector Array Calculations

The calculations of solar energy collected labeled Array #1, Array #2 and System are based on three different temperature difference measurements. The system calculation should not be interpreted as the sum of the two array calculations. "Incident solar" is the total solar energy incident on the collectors over the entire day and "fraction over day" is the fraction, in percent, of the total incident solar that is collected.

In August, the System energy collected calculation is the sum of the two individual Array values. Because of drift in the calibration of one of the sensors used in the "System" calculation, the composite of the two individual Array's calculations is used to improve accuracy.

Boiler Calculations

The estimated efficiency of 70% is a single value approximation of the overall energy efficiency of the boiler loop.

Hot Reservoir Calculations

The loss through the insulation is calculated by performing an energy balance on the other items listed which are directly measured.

Absorption Chiller Calculations

Energy directed to the chillers is thermal energy only for driving the absorption cycle.

Cold Fan Coils and Coil Reservoir Energy Calculations

The cold reservoir energy loss is calculated by an energy balance on the chillers' cold water output, the Cold Fan Coils (CFC) energy use and the energy change of the cold reservoir. The negative tank loss in August is due to the fact that for heavy cooling load months, the cold tank loss is small compared to the error in energy measurement.

The very small numbers listed for CFC Bypass cooling are due to accounting for energy flows during switches in cooling system mode of operation.

Distribution of Solar Energy

This distribution uses the value calculated vs."System" energy collected as a basis.

Distribution of Hot Reservoir Energy

This distribution uses the energy output of the hot tank as a basis. The low value of the sum indicates the high line losses present during low demand operation of hot reservoir based heating.

Total Energy Loads

"Water Side" refers to those energies measured in the fluid loops delivering energy to the heating and cooling fan coil units.

"Solar Energy Utilized by System" is the sum of all the solar derived energy actually used to heat and cool the building and heat the domestic hot water. "Boiler Energy Utilized by System" is the same sum for boiler derived energy.

"Operating Electric Energy" includes all uses of electric energy by the system but does not include lights, office equipment, etc.

"Total Energy Consumed" is the sum of solar energy collected and gas and electric energy used by heating cooling system.

"Solar Fraction of Building Load" is the fraction of solar derived energy used in the fluid loops supplying energy for heatng, cooling and DHW to the building.

"System Performance Factor," the fossil fuel expended, refers to the sum of the gas energy consumed and the gas energy necessary to generate the electric energy consumed at an assumed generating plant efficiency of 40%. The total energy delivered to the building load is the sum of the energies supplied to the hot and cold fan coils and to the DHW system.

The last six calculations defined are explained in more detail in "Thermal Data Requirements Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program," originally published as an ERDA report.

These calculations are those made at midnight by the DAS, based on the summaries of real time performance calculations.

<u>Daily Performance Calculations</u>

NO	ITEM
1	Total energy input to the building-solar plus boiler
2	Total energy input to the hot reservoir from all sources
3	Total energy input to the primary side of the heat exchanger from all sources
4	Total energy output through the primary side of the heat exchanger
5	Total energy input to the primary side of the heat exchanger from boiler energy
6	Total energy input to the primary side of the heat exchanger from solar energy

7 Energy output through secondary side of the heat exchanger from boiler energy

8 Energy output through secondary side of the heat exchanger from solar energy

9 Energy output through primary side of the heat exchanger from boiler energy

10 Energy output through primary side of the heat exchanger from solar energy

11 Energy delivered to HFC* from the hot reservoir that was boiler originated

12 Energy delivered to the HFC from the hot reservoir that was solar originated

13 Energy delivered to the CFC** from the cold reservoir that was boiler originated

14 Energy delivered to the CFC from the cold reservoir that was solar originated

15 Daily cold reservoir energy change

16 Daily hot reservoir energy change

17 Daily energy loss from hot reservoir

18 Daily energy loss through insulation from hot reservoir

19 Cold storage reservoir daily efficiency

20 Hot storage reservoir daily efficiency

21 Total building space heating, cooling, DHW energy

22 Heating energy to building

23 Cooling energy to building

24 Percent of heating energy supplied by solar

25 Percent of heating energy supplied by boiler

26 Percent of cooling energy supplied by solar

27 Percent of cooling energy supplied by boiler

28 Percent of cooling energy supplied by economizer

29 Percent of DHW load supplied by solar

30 Percent of DHW load supplied by boiler

31 Percent of energy supplied to building load supplied by solar

---

* HFC - Hot surface in air handlers

** CFC - Cold surface in air handlers

Percent distributions of solar energy collected to:

32 Heat exchanger
33 HFC
34 HFC (bleed)
35 Chillers
36 DHW

Percent distributions of boiler energy produced to:

37 Heat exchanger
38 HFC
39 Chillers
40 DHW

Percent distributions of hot reservoir energy to:

41 HFC
42 DHW
43 Total heating energy used by the zones

APPENDIX C

CALCULATION OF ESTIMATED ENERGY REQUIREMENTS OF TWO NON-SOLAR SYSTEMS

C.1 VAPOR COMPRESSION COOLING SYSTEM (SYSTEM 2)

A conventional heating and cooling mechanical design for the Community Center had been selected before the final approval for the Solar Energy Project was made. This system is used as the basis for estimating the auxiliary (gas and electric) energy used by a "conventional" system. The design is shown in Figure C.1. The components shown in Figure C.1 are:

- ° Vapor Compression Chiller--Chrysler HWW60-X, 61.7 tons capacity, 58.6 KW input, 3.7 rated COP
- ° P1 - Cold Fan Coil Pump, 2 HP
- ° P2 - Hot Fan Coil Pump, 2 HP
- ° P3 - Condensing Water Pump, 1.5 HP
- ° Boiler--9.6×10^5 Btu/hr output
- ° Cooling Tower with fan driven by 2 HP motor

C.1.1 Gas Use Calculation for Conventional System

To estimate the gas use of this "conventional" system, information on operation of the existing solar system is used. In the conventional system, all thermal energy for heating is provided by the gas boiler. Its gas use can be estimated using the measured total thermal energy supplied for heating from both the boiler and solar and the observed efficiency of the boiler/boiler loop for each month.

Domestic hot water for the conventional system would have been provided by a typical gas fired water heater. Its gas use is estimated by the measured thermal energy supplied for domestic hot water divided by an assumed thermal efficiency for a water heater of 70%.

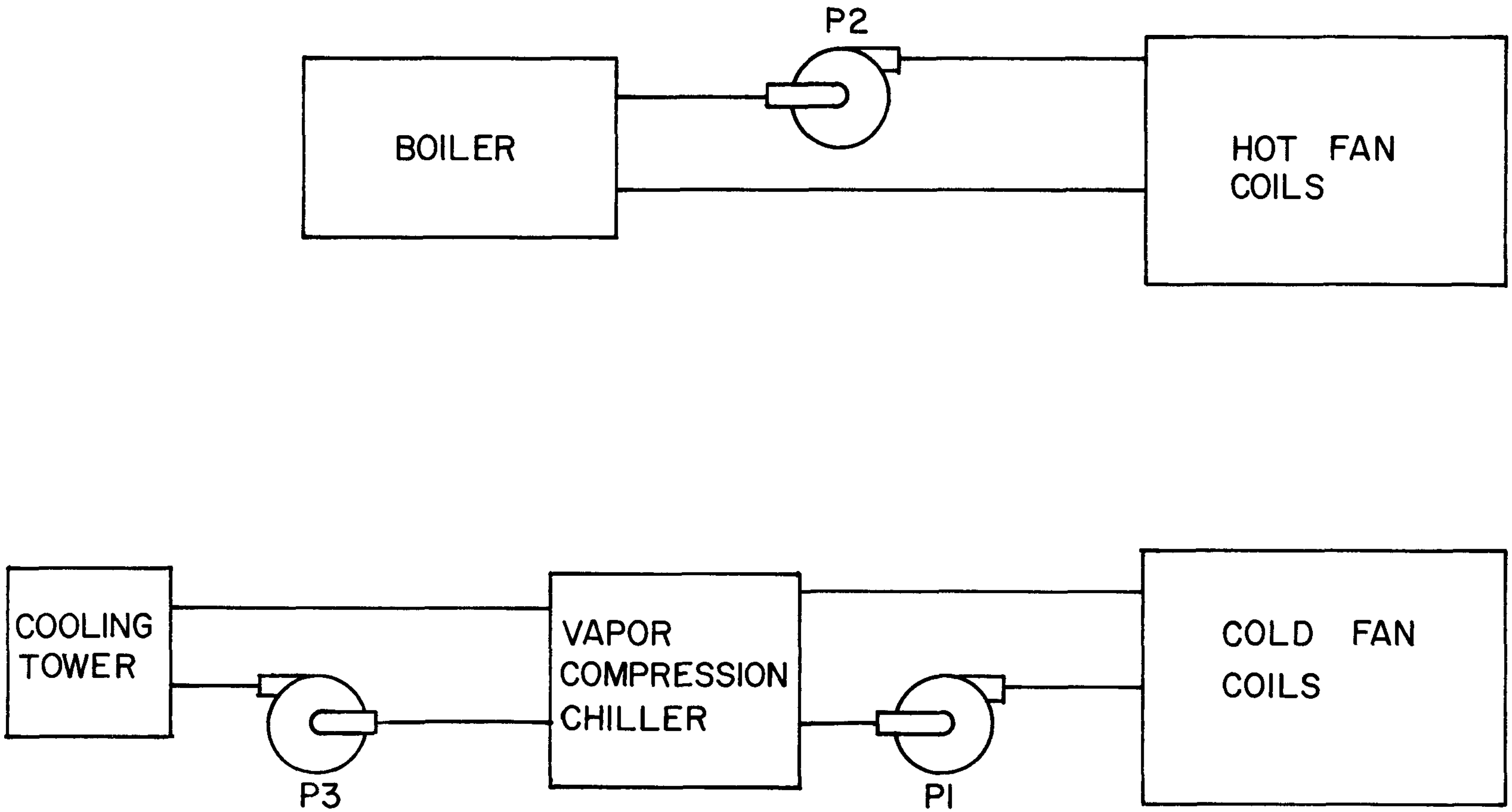


FIGURE C.I. - LINE DIAGRAM OF ORIGINAL HVAC SYSTEM

The equations used are:

$$E_{gas_{heat}} = E_{heat_{meas}} / \eta_{boiler}$$

$$E_{gas_{DHW}} = E_{DHW_{meas}} / \eta_{DHW}$$

where

$E_{gas_{heat}}$ = Gas energy used by conventional system for heating.

$E_{heat_{meas.}}$ = Total measured thermal energy used for heating.

$E_{gas_{DHW}}$ = Gas energy used by conventional system for domestic hot water.

$E_{DHW_{meas.}}$ = Total measured thermal energy used for domestic hot water.

η_{DHW} = Thermal efficiency of typical water heater, assumed to be 0.7.

η_{Boiler} = Thermal efficiency of boiler, set at 0.7, based on observations of the existing system.

C.1.2 Electrical Energy Use Calculations for Conventional Systems

Electric energy use is estimated using measurements of running times of pumps and the total demand for cooling energy in the existing system. Running times of the two fan coil pumps would be the same in both systems; therefore, the energy used by these two pumps in the conventional system is calculated as the product of their rated power and the running times in the existing system.

For calculation of the length of time of operation of the condensing water pump and the cooling tower fan, it is assumed that the fan operates whenever the pump is on. Also it is assumed that the condensing water pump operates whenever the chiller is operating, as is true with the existing system. Since the vapor compression chiller has a higher capacity than the existing absorption chillers, the vapor compression chiller would operate for a shorter length of time. The length of time of operation is assumed to be the product of the ratios of the capacities of the two chillers and the length of time of operation of the absorption chillers.

The electric energy use of the chiller itself is calculated as the total measured cooling load divided by an average operating C.O.P. for the unit. The rated C.O.P. is 3.7 but a C.O.P. of 3.0 is assumed to account for inefficiencies inherent in actual operation.

The equations used are:

$$E_{P1} = (T_{P5})\ (P_{P1})$$

$$E_{P2} = (T_{P3})\ (P_{P2})$$

where

T_{Pi} = Running time for pump "i" in existing system

P_{Pi} = Rated power of pump "i" in conventional system

E_{Pi} = Electric energy consumption of pump "i" in conventional system

and

$$E_{cw} = (P_{cw})(T_{ch1} + T_{ch2})\ \left(\frac{25\ \text{tons}}{61.7\ \text{tons}}\right)$$

where

E_{cw} = Electric power use of condensing water pump and cooling tower fan

P_{cw} = Rated power of condensing water pump and cooling tower fan

T_{chi} = Running time for chiller "i" and

$$E_{ELC_{cool}} = \frac{E_{cool_{tot}}}{COP_{av}}$$

where

$E_{cool_{tot}}$ = Total cooling load

COP_{av} = Average operating COP of vapor compression unit

$E_{ELC_{cool}}$ = Electric energy used for cooling (energy consumption of chiller).

C.2 BOILER FIRED ABSORPTION SYSTEM (SYSTEM 3)

A second non-solar alternative system is considered, one in which absorption chillers are used and all thermal energy for the system is supplied by a gas-fired boiler. It would be essentially the existing system without the solar collectors and the hot storage tank and their respective pumps: P1, P2, P2A and P10.

6.2.1 Gas Use Calculation for Boiler Fired Absorption System

The gas energy used for heating and domestic hot water would be the same as for the vapor compression system. The gas energy used in driving the absorption chillers would be calculated in a similar manner, the gas energy required would be the total measured thermal energy needed to drive the chillers in the existing system divided by the observed thermal efficiency of the boiler/boiler loop for each month.

The equation used is:

$$E_{gas_{chl}} = \frac{E_{chl_{meas}}}{\eta_{boiler}}$$

where

$E_{gas_{chl}}$ = Gas energy used to drive the absorption chillers

$E_{chl_{meas}}$ = Total measured thermal energy consumed as firing water by the absorption chillers

C.2.2 Electrical Energy Use Calculation for Boiler-Fired Absorption System

For a boiler-fired system, the electrical energy use would be that for the existing system minus the electrical energy used by the omitted pumps. The longer running time of the boiler loop pump (P9) must be accounted for. The increase is proportional to the ratio of the gas use of the boiler in a boiler-only system to the gas use in the existing system.

The equation used is:

$$E_{ELC_{boiler}} = E_{ELC_{solar}} - E_{P1} - E_{P2} - E_{P2A} - E_{P10} + (E_{P9})\left(\frac{E_{gas_{boiler}}}{E_{gas_{solar}}}\right)$$

where

E_{Pi} - Electric energy use of pump "i" in the existing system

$E_{ELC_{solar}}$ - Total electric energy use in the existing system

$E_{ELC_{boiler}}$ - Total electrical energy use by the boiler only system

$E_{gas_{solar}}$ - Gas use of the solar energy (existing) system

$E_{gas_{boiler}}$ - Gas use of the boiler only system

C.3 CALCULATION OF AUXILIARY ENERGY USE OF A SOLAR ABSORPTION CHILLING SYSTEM WITH VAPOR COMPRESSION BACKUP FOR THE SIX MONTHS COOLING SEASON

GAS

For heating, gas use would be the same as for the present system minus the gas used to operate chillers.

HEATING	60.14×10^6 Btu
COOLING	0.0
DHW	8.94
	69.08

ELECTRIC ENERGY

A vapor compression unit would function as backup; therefore, it would provide the cooling energy supplied in the present system by boiler operation of chillers. Therefore, the electric energy use for cooling would be:

Electrical energy required for vapor compression backup operation over six months cooling season

$$= \frac{\text{Cooling energy required during backup operation}}{\text{COP of vapor compression chiller}}$$

$$= \frac{149.72 \times 10^6}{3.0}$$

$$= 49.6 \times 10^6 \text{ Btu}$$

Pumps 6,7 and 9 would run less because the chillers and boiler would run less. From time length outputs the chillers would run 43% shorter time. The boiler would burn 87% less gas. The net effect would be 12.5 million Btu less auxiliary electric energy used. However, the cooling tower pumps and fan for the vapor compression chiller would require additional electric energy use. This is estimated, based on how much backup cooling is required and the unit's capacity, to be an extra 12,200 minutes of operation or 4.9 million Btu extra electric energy required. The net decrease in auxiliary electric energy demand would be 7.6 million Btu. The total values would be:

AUXILIARY	125	$\times 10^6$ Btu
AIR HANDLERS	151	
TOTAL	276	

NET FOSSIL FUEL* CONSUMPTION: 1000.0

(All above values are in millions of Btu)

*Assuming an electric generating plant efficiency of 35%.

APPENDIX D

DEVELOPMENT OF A COMPUTER SIMULATION MODEL

When Lockheed Palo Alto Research Laboratory designed the solar system for the Santa Clara Community Recreation Center, it developed a computer simulation model which was capable of simulating the overall thermal energy demands of the system (see Figures 12 and 13.) As part of the present work, the University of Santa Clara has continued the development of the computer model for the thermal response of the system. Electrical demands of the system are not modeled. It is expected that the present unique data acquisition system will make it possible to accurately refine the computer simulation model. Expected uses for the model are discussed below.

D.1 THE COMPUTER PROGRAM

The construction of the present computer simulation program involves the following tasks:

1. Development of new or adaptation of previously written computer subroutines which model the thermal response of the system components.

2. Definition of the control logic built into the physical system.

3. Development of the overall code based on the elements produced above.

4. Assembly of the variable input data.

5. Refinement of the model.

Tasks 1-3 have been completed. Work is now being done on tasks 4 and 5.

The computer program is composed of a main program entitled SCCC (Santa Clara Community Center) and three subroutines--VORTA, COLL and STRAT. The main program is used to read in data, print out the input data and

and call the simulation subroutine VORTA. VORTA is the main simulation routine. It senses building thermal demands, determines the state of the system and responds according to the system control logic. VORTA contains two major iteration loops. The outer loop simulates the response of the system for units of time selected by the user.

When the program is first called the demand conditions are initialized to an OFF condition or ZERO demand status. Then a series of operating and demand conditions are established. The building load model is exercised for each of the four zones:

Lobbies and Halls	North Side Rooms
South Side Rooms	Multi-purpose Rooms

The conditions for the low solar mode are tested and, if satisfied, the low-solar mode is set (INSOL=1) and subroutine COLL (collector) is called to model the output of the collector array. The ballast tank is modeled next since its temperature (D2) provides a test condition for many of the events which follow. The conditions for high-solar mode and tested and if satisfied the high-solar mode is set (INSOL=2.)

Subroutine VORTA also test for flow circulation and component functions. Then, those demand conditions which are not dependent upon building zone temperatures are set.

The inner loop of VORTA simulates each of the four building zones. In each zone, the heating-cooling-economizer status is determined and the appropriate temperature adjustments are made. In addition, the demand conditions on the various components are set depending upon the conditions in each zone. These conditions are then modeled and the status of the components is caused to change as the program cycles through the various zones. In the last section of the outer loop, the status of the system flow circulation is examined to determine the input source for the collector array.

D.2 ASSEMBLY OF THE INPUT DATA AND REFINEMENT OF THE MODEL

Virtually all of the data used in this simulation model is introduced in the form of variable inputs. Since the physical system has been completed and is in operation, it might appear that much of the data could be written into the program as constants. However, the practice of entering all data through a variable input list has two principal advantages. Modification of the actual system can be reflected easily in the simulation model and exploratory or comparative studies can be made through the variation of physical factors and elements of the control logic.

In a complex system such as the one being modeled in this instance, it is difficult to precisely describe the operation of the system. The description of the manner in which the system operates is limited by the understanding of the operation and interaction of the component elements. The simulation model is similarly bounded by the ability to relate these system operations to a program routine.

The tuning process has the theoretical goal of matching the simulation model to the performance of the actual system. In practice, this is a process of modification and upgrading of the model in response to the increasing understanding of the manner in which the system functions as obtained from the data acquisition system. Obviously, the tuning process can only be undertaken in conjunction with a complete operating system. On the other hand, this aspect of the simulation effort is leading to a better theoretical understanding of fully-coupled dynamic systems and is providing a significant contribution to the art of simulating energy systems.

D.3 UTILIZATION OF THE SIMULATION MODEL

The purpose in constructing a solar energy system simulation model is to provide capabilities for examining the performance of the existing system, predicting performance for different input parameters, and examination of the limits of the operating range of the system. As a part of the tuning process, the simulation model is being run with actual data to isolate and refine the factors which make up the description of different components. This is a two-way activity. Since the system is operating effectively, the actual data represents the output which the simulation model must be very nearly reproduce. In the process of reproducing the output data for a given set of input conditions, we will isolate and examine each data element with respect toits effect upon other elements in the system.

The simulation model can be used to develop sensitivity information and cost data relative to component sizing and variation of performance modes and operating limits. In this respect, the Santa Clara Community Center solar energy system can be utilized to determine the effects of variation of component sizes, flow rates, threshhold sensor settings, and operating modes. Although predictive capabilities of the model will primarily benefit the design and analysis of other systems, there are two areas in which the simulation model can provide unique predictive data for this system. The first is the examination of a variety of weather data. The actual system has only been operated in what is apparently an extremely unusual year from the standpoint of weather. Using the simulation model, the system performance can be examined using the weather from previous years with limited periods in which unusual runs of weather have occurred, and artificially introduce weather patterns designed to exercise the system under extreme conditions. The other area is one in which the simulation model may provide the only source of data--examination of the limits of the operating range. The system design includes a number of protective features such as prevention of freezing in the chillers, bleed mode, and dump mode. These are abnormal situations which probably would not be initiated by normal weather patters. Using the simulation model, it will be possible to cause such events, and then examine the system operation approaching the onset of a protective situation and the system responses. Examination of the operating envelope will provide a confirmation of the present design or indicate areas requiring design review.

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