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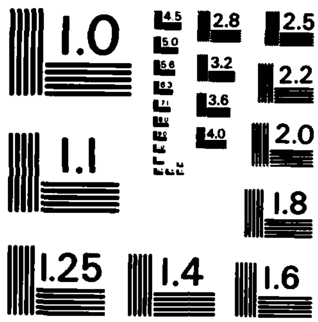

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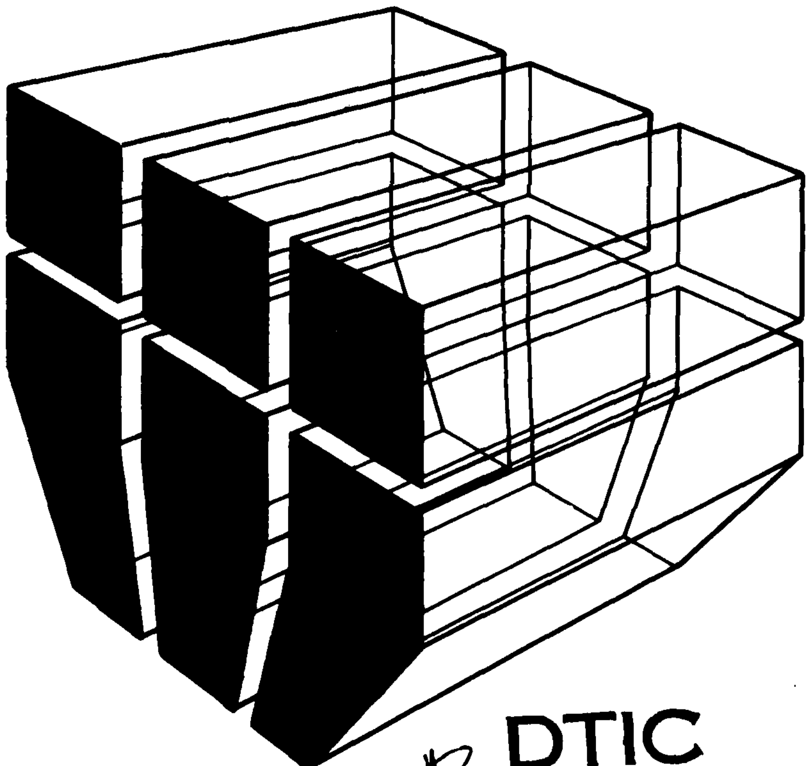
TECHNICAL REPORT E-202
September 1984

EVALUATION OF THE MEASURED ENERGY PERFORMANCE OF FOUR SOLAR SYSTEMS



by
D. L. Johnson
D. C. Hittle

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This report describes the measured energy performance of four solar systems installed in military construction. Based on measured performance for a period of about 1 year, none of the solar systems provided the energy savings expected from the design calculations. When the fuel cost savings produced by the solar components of the systems were compared with the added solar costs, the solar systems had simple payback periods of more than 25 years.

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The field problems for the solar systems revealed by the study are discussed and related to system performance. The performance of all four systems suffered from control failures and excessive operation and maintenance (O&M) requirements.

It was concluded that reliable, efficient designs must be simple and based on proven technologies. Recommendations for improving future solar designs are presented. [illegible]

FOREWORD

This work was performed under Reimbursable Orders IAOE878-0065, -0066, -10101, and IA0887790041 for the Fort Worth District, Southwestern Division, U.S. Army Corps of Engineers. Mr. O. L. Osborne served as the point of contact (POC) at the Fort Worth District. The POCs at the sites were Mr. B. Gibbons (Seagoville, TX), Mr. D. Dark (Albuquerque, NM), and Mr. B. Hobbs (Fort Hood, TX).

This study was performed by the Energy Systems (ES) Division of the U.S. Army Construction Engineering Research Laboratory (CERL). Mr. R. G. Donaghy is Chief of CERL-ES.

Appreciation is expressed to Dr. David Joncich for his leadership during this project. Appreciation is also expressed to Dr. Chang Sohn for his help with writing the computer programs, to Ms. Katherine Beauchamp for her aid with the data analysis, and to Mr. Lee Edgar and Mr. Maurice Hurst for their assistance with data collection. A special thanks is extended to onsite personnel who helped with this study: Mr. A. R. Penn at Seagoville, Mr. Nelson Budd at Albuquerque, and Mr. Michael Jordan at Fort Hood.

COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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CONTENTS

CONTENTS (Cont'd)

TABLES

FIGURES

EVALUATION OF THE MEASURED ENERGY PERFORMANCE OF FOUR SOLAR SYSTEMS

1 INTRODUCTION

Background

Federal regulations require that designers consider including solar energy systems in the design of new military construction.[1] These regulations are intended to help conserve scarce conventional resources by deriving energy from the sun for applications in which the addition of solar components is cost effective.

To determine how cost effective a solar system is for a potential application, the designer evaluates the tradeoff between the expected energy savings and the added costs of the solar portion of the system. Although design methods have been developed for this type of application, the actual performance of solar systems operating in the field may differ if the design criteria are not met.[2] Hence, actual energy performance must be measured to directly establish how much energy is saved by using solar systems.

In addition to providing a measured value for the energy savings for a specific solar design at a specific site, measured energy performance can also be compared with the designers' predictions. This comparison allows design methods to be refined to reflect more realistic field operating conditions. Using comparison data to verify solar designs also allows the measured results to be extended to a wide range of solar applications.

To meet this need to verify solar system design by measuring actual energy performance, the Fort Worth Engineer District and the Southwestern Engineer Division of the U.S. Army Corps of Engineers asked the U.S. Army Construction Engineering Research Laboratory (CERL) to help measure and evaluate the energy savings provided by four solar systems used by the Fort Worth District in four military construction projects. The four systems had been installed to demonstrate how solar technology could be used to conserve energy in military construction. The sites included in the monitoring program were: (1) the U.S. Armed Forces Reserve Center at Albuquerque, NM; (2) the U.S. Army Reserve Center at Seagoville, TX; (3) the Two Battalion Headquarters and Classroom Building (Bldg No. 29015) at Fort Hood, TX; and (4) the EM Barracks Building (Bldg No. 14015) at Fort Hood.

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[1] Code of Federal Regulations, 10 CFR 436A (Updated periodically).

[2] D. M. Joncich, D. J. Leverenz, D. C. Hittle, and G. N. Walton, Design of Solar Heating and Cooling Systems, Technical Report E-139/ADA062719 (U.S. Army Construction Engineering Research Laboratory [CERL], 1978); and G. Franta, et al., Solar Design Workshop, SERI/SP-62-308 (Solar Energy Research Institute and Los Alamos Scientific Laboratory, 1981).

Objective

The objective of this study was to measure and evaluate the energy savings of four solar systems incorporated in military construction by the Fort Worth Engineer District.

Approach

To help the Fort Worth District with the solar monitoring, CERL performed the following steps:

1. Defined the measurements needed to evaluate the performance of the solar systems.

2. Devised an instrumentation plan for each system to enable such measurements to be conducted.

3. Prepared and sent instrumentation plans to the Fort Worth District to enable some hardware to be installed by the construction contractor, and procured and installed other electronic hardware as needed.

4. Visited the sites during construction to help the resident engineer inspect the solar systems and monitor the hardware.

5. Operated the monitoring equipment used to collect, transmit, and store the measurement data.

6. Notified the Fort Worth District and the onsite point-of-contact (POC) when onsite monitoring equipment needed maintenance or repair.

7. Helped onsite personnel operate and maintain the solar systems when problems arose.

8. Analyzed the data to evaluate the performance of the solar energy systems.

Scope

The monitoring described in this report focused on the performance of the solar components in each system. However, the energy savings from the solar components normally depend on the operation of some conventional HVAC components. Consequently, it was also necessary to examine the performance of some conventional HVAC components during this study.

Since the performance of a particular solar system depends on many factors (the specific design, onsite weather conditions, the conditions under which it was operated and maintained, etc.), the quantitative results given in this report cannot be directly applied to other solar designs or solar systems operating under different conditions.

Mode of Technology Transfer

It is recommended that the results of this study be incorporated into the Corps of Engineers Guide Specification 13985, Solar Equipment and the Army Technical Manual 5-804-2, Solar Energy Systems.

2 DESCRIPTION OF THE SOLAR SYSTEMS

The four solar systems included in this monitoring study were:

1. U.S. Armed Forces Reserve Center at Albuquerque, NM

2. U.S. Army Reserve Center at Seagoville, TX

3. Two Battalion Headquarters and Classroom Building (Bldg No. 29015) at Fort Hood, TX

4. EM Barracks Building (Bldg No. 14015) at Fort Hood.

Table 1 briefly summarizes the characteristics of each of the four solar systems monitored by CERL. The systems ranged from a simple domestic hot water (DHW) system with a 3470-sq ft collector array for the EM Barracks Building at Fort Hood to a complex system (space heating and cooling, DHW heating) with a 12,050-sq ft* collector array at the Seagoville Reserve Center.

Design calculations for each system were done by Architectural/Engineering (A/E) firms under contract to the Fort Worth District. All four of the designs were produced by integrating solar components and conventional HVAC and water heating components to form a solar system. Such systems are called "solar-assisted" because the solar components are expected to supply only part of the total building load, with the remainder to be supplied by conventional components (i.e., the conventional components backup the solar ones). In Table 1, the column entitled "Function of Solar" lists the fraction of the building loads that should be supplied by the solar components according to the A/E's design calculations. For example, the A/E calculated that the solar components would supply 100 percent of the DHW heating, 100 percent of the space heating, and 98 percent of the space cooling for the Albuquerque building.

Table 2 lists the heating and cooling degree days for the three sites. These data were taken from a standard reference book.[3] Note that the two reserve centers, which had similar designs, operated under markedly different weather conditions. For example, Albuquerque had almost twice as many heating degree days as Seagoville, but the situation was reversed for cooling degree days.

Albuquerque Reserve Center

This 600-man reserve center is used jointly by the Army, Navy, and Marine Corps. The two-story building has 55,240 sq ft of floor area. The exterior walls are precast concrete wall panels with a rake finish. The building has a standard built-up roof.

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*Metric Conversion Table is on p 81.

[3]C. Knapp, T. Stoffel, and S. Whitaker, Insolation Data Manual, SERI/SP-755-789 (Solar Energy Research Institute [SERI], 1980).

Table 1

Solar System Characteristics Summary

Building	Floor Area (sq ft)*	Function of Solar	Collector Array Area and Type (sq ft/type)	Storage Tank(s) (gal)	Special Notes
600-man Reserve Center at Albuquerque, NM	55,240	100% DHW** 100% H** 98% C**	10,600 flat plate, singly-glazed (Sunworks)	20,000 HW+ 20,000 CW+	HVAC system includes heat recovery system using reciprocating chiller and CW tank; has many wintertime modes of operation.
300-man Reserve Center at Seagoville, TX	30,694	98% DHW 100% H 94% C	12,050 flat plate, singly-glazed (Sunworks)	15,000 HW 15,000 CW	HVAC system almost identical to Albuquerque, except for component sizes which were adjusted to match predominant cooling load.
Two Battalion Hq and Classroom Bldg at Fort Hood, TX	12,300	98% H 83% C	5,663 flat plate, doubly-glazed (GE alum.)	15,000 HW 2,000 CW	Backup for solar is steam and chilled water from central plant; controls design features timing to meet transient peak demands with backup; original design modified to improve solar cooling.
EM Barracks at Fort Hood (Capacity = 173 persons).	51,400	DHW++	3,470 flat plate, doubly-glazed	6000 HW	Backup is steam-fired generator; system installed as part of EM Barracks modernization project.

*Metric conversion: 1 sq ft = 0.092 m^2; 1 gal = 3.7 L.
**DHW = domestic hot water (H = space heating, C = space cooling).
+HW = hot water storage tank; CW = cold water storage tank.
++The solar fraction was calculated to be 70% for the original design, but kitchen facilities were added later.

Table 2

Average Weather Conditions at Each Site

Monitoring Site	Heating Degree-Days	Cooling Degree-Days
Albuquerque, NM	4291	1316
Seagoville, TX	2290	2754
Fort Hood, TX	1850	2900

Figure 1 is a schematic of the solar-assisted HVAC system at this site. The schematic shows that the system has a large number of piping interconnections and automatic control valves. Hence, the operation of this system is quite complex. The major features of the system are:

- A four-pipe fan-coil system to distribute heating and cooling to the zones
- Solar components which help with space heating, space cooling, and DHW heating
- Four sources of space heat during the heating season
- A reciprocating chiller which operates as a heat pump in conjunction with a 20,000-gal cold water (CW) storage tank to provide space heating
- Cooling by an absorption chiller powered by solar with a reciprocating chiller as backup
- An energy monitoring and control system (EMCS) to provide monitoring, load-shedding, and other control functions.

The operation of this HVAC system in the wintertime modes is especially complex because of the many different space heating sources and because these multiple sources operate simultaneously under certain conditions. The heating source in the wintertime modes of operation varies as follows:

- Waste heat recovered from the heat pump condenser during wintertime cooling and stored in the CW storage tank
- Direct solar heating from the hot water (HW) storage tank
- Low-temperature water from the HW tank with reciprocating chiller operating as a solar-assisted heat pump
- DHW boiler (natural gas) used to boost the water supply temperatures when needed.

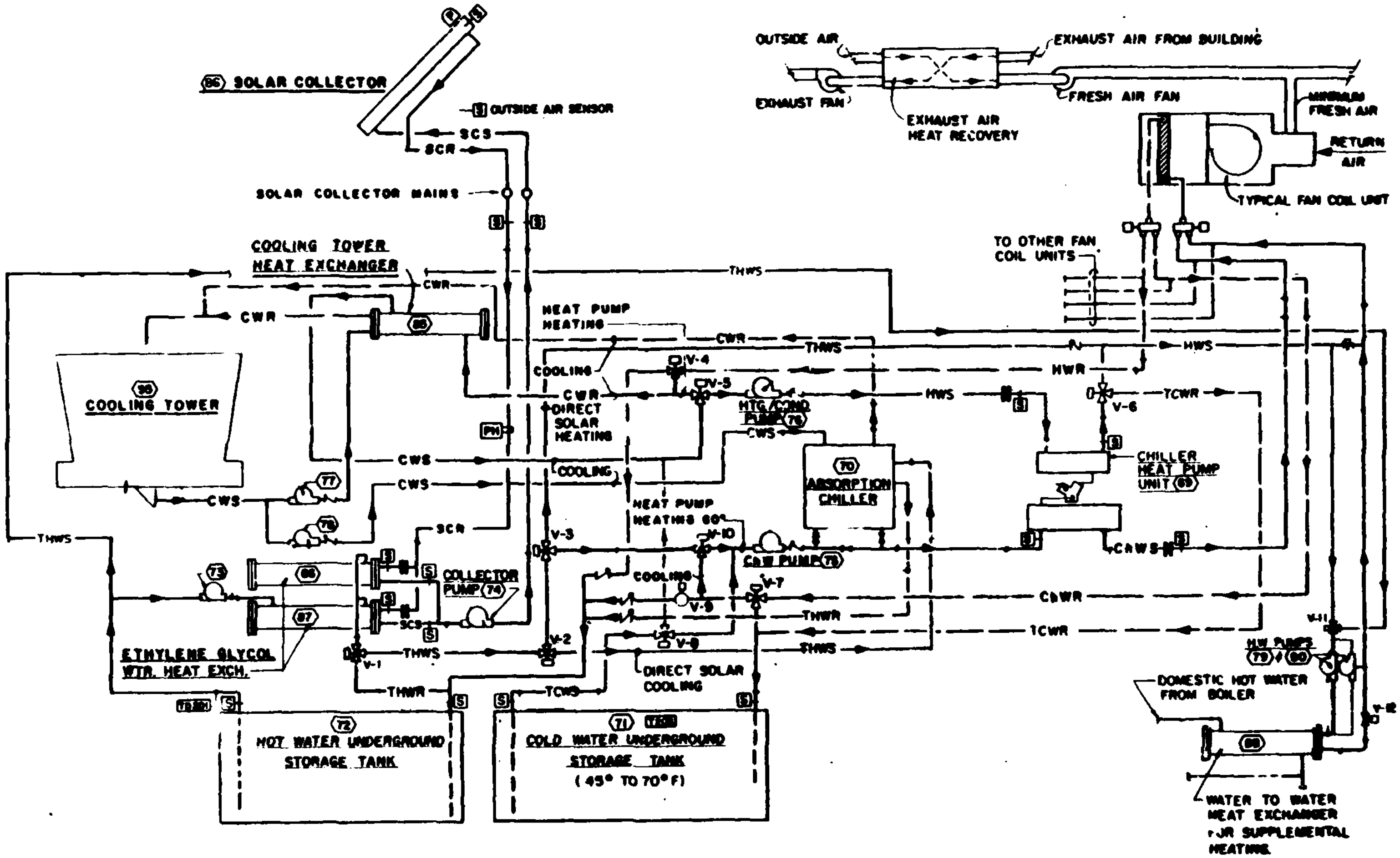

Figure 1. Schematic of the solar system at Albuquerque site.

The design calculations by the A/E firm indicated that the direct solar heating would supply 100 percent of the heating for the building for the weather conditions specified. The other heating modes were added as "emergency" sources of heating during extreme weather conditions. The natural gas consumption of the DHW boiler was calculated to be zero for the entire year. The electrical energy consumption of the reciprocating chiller was listed as 3760 kWh per year to supplement solar cooling (i.e., a cost of about ($220 per year).

Seagoville Reserve Center

This 300-man reserve center, used by the U.S. Army Reserves, is a one-story structure with 30,694 sq ft of floor area. The building has a brick-faced exterior and a standard built-up roof.

This building has an HVAC system that is almost identical to the Albuquerque building, except for the following:

- The collector array is roughly 20 percent larger and both storage tanks are 25 percent smaller (to accommodate the predominant cooling load).

- Other HVAC component sizes differ to accommodate the different loads of this building.

- The DHW boiler uses fuel oil.

With the predominance of cooling at the Seagoville site, the design calculations by the A/E firm indicated that this solar system would provide 100 percent of the space heating with "room to spare." Indeed, the minimum tank temperature listed in the computer study was 147°F in January and averaged 187°F, a value far in excess of the 105°F minimum needed to provide space heating directly from the solar system. The study indicated that the absorption chiller would be providing space cooling (operating in the summertime mode) from February through the middle of December and provide 94 percent of the space cooling load.

The annual fuel oil consumption of the DHW boiler was figured as 8.166 MBtu* (about $50). The annual electricity consumption of the chiller was figured to be 12,917 kWh (about $710).

Fort Hood Battalion Headquarters and Classroom Building

This one-story structure has 12,300 sq ft of floor area. The HVAC system at this site is simpler than the ones at the two reserve centers (Figure 2). Notable features of this system are:

- A central air handler with four separate coils (solar heating, solar cooling, conventional heating, and conventional cooling).

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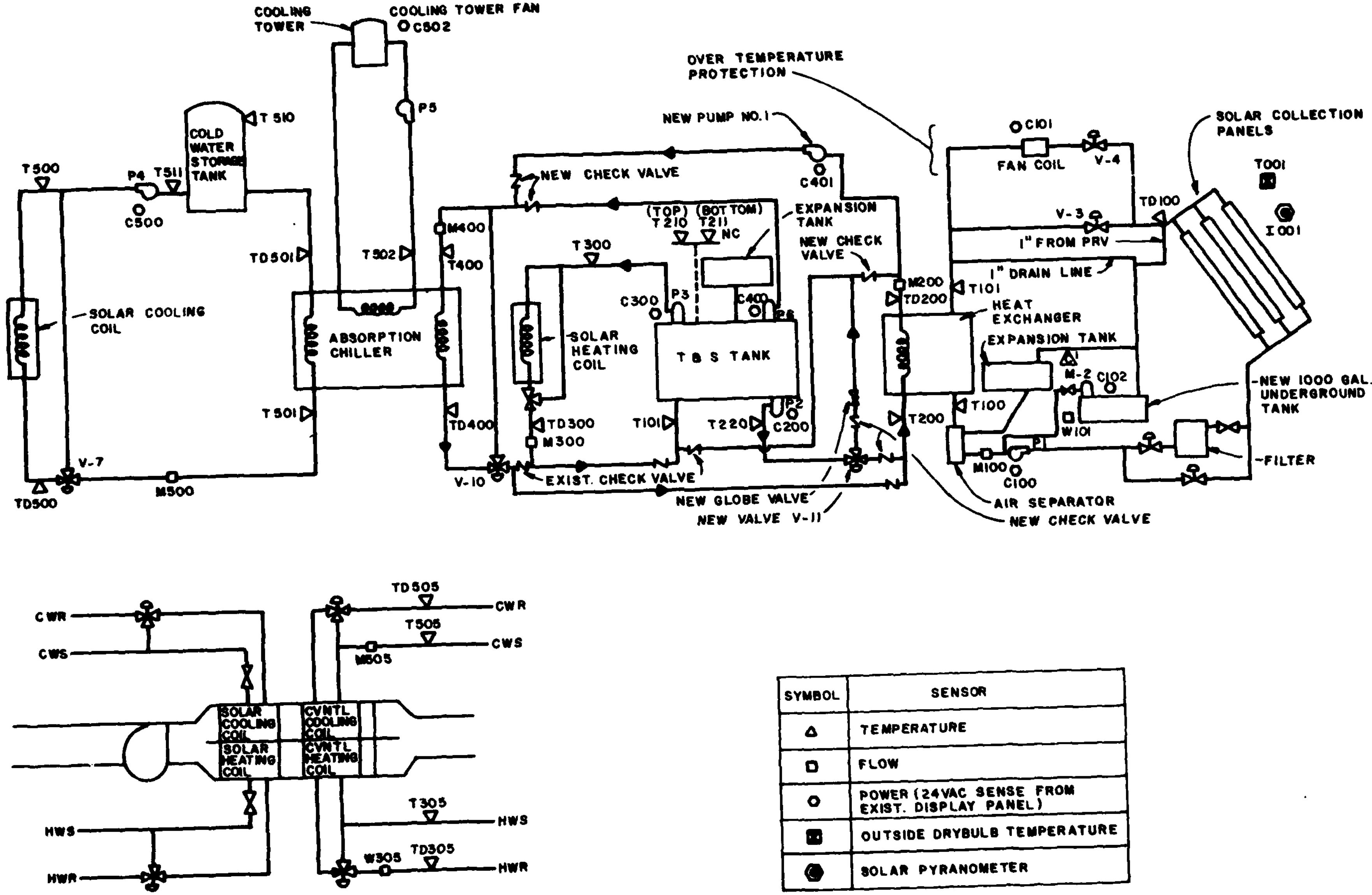
*MBtu = 10^6 Btu.



SYMBOL	SENSOR
△	TEMPERATURE
□	FLOW
○	POWER (24VAC SENSE FROM EXIST. DISPLAY PANEL)
■	OUTSIDE DRYBULB TEMPERATURE
⬢	SOLAR PYRANOMETER

Figure 2. Schematic of solar-assisted HVAC system at Battalion Headquarters Building at Fort Hood.

• Backup for the solar system is steam and chilled water from a central plant.

• Although the HVAC system is rather simple, the controls were designed with special timing features to meet transient peak demands.

• The original design was modified to improve solar cooling performance (the storage tank was bypassed to drive the absorption chiller directly from the solar heat exchanger).

The concept study predicted that the solar components would supply 98 percent of the space heating and 83 percent of the space cooling needs for the building. No DHW heating was included in the system design. This building had been operating for some time before the start of the monitoring study.

Fort Hood EM Barracks Building

This three-story building has a capacity for 173 persons and 51,400 sq ft of floor area. The solar system was retrofitted as part of the EM Barracks Building Modernization project at Fort Hood.

The solar components in this building help with DHW heating. The solar backup is a steam-fired generator supplied from a central plant. Figure 3 is a schematic of the solar system, which is a standard type in which city water is preheated before delivery to the conventional DHW system. Special features of the system include:

• Dual solar storage tanks

• Special control strategy for solar collection which allows sequential use of the solar storage tanks

• A heat purge unit located on the roof to prevent over-temperature conditions in the solar collectors.

The concept study by the A/E firm indicated that the solar components would supply 70 percent of the hot water requirements of the building and save the energy equivalent of 1076 million cu ft of gas. However, kitchen facilities were added to the building after the design calculations were completed. The additional HW consumption would be expected to produce, on the average, a lower operating temperature for the solar collectors. Since the collector efficiency is higher at the lower operating temperatures, the added load would actually increase the energy savings provided by solar, even though the solar fraction would be smaller than the design value.

This building had been operating for some time before the start of the monitoring study.

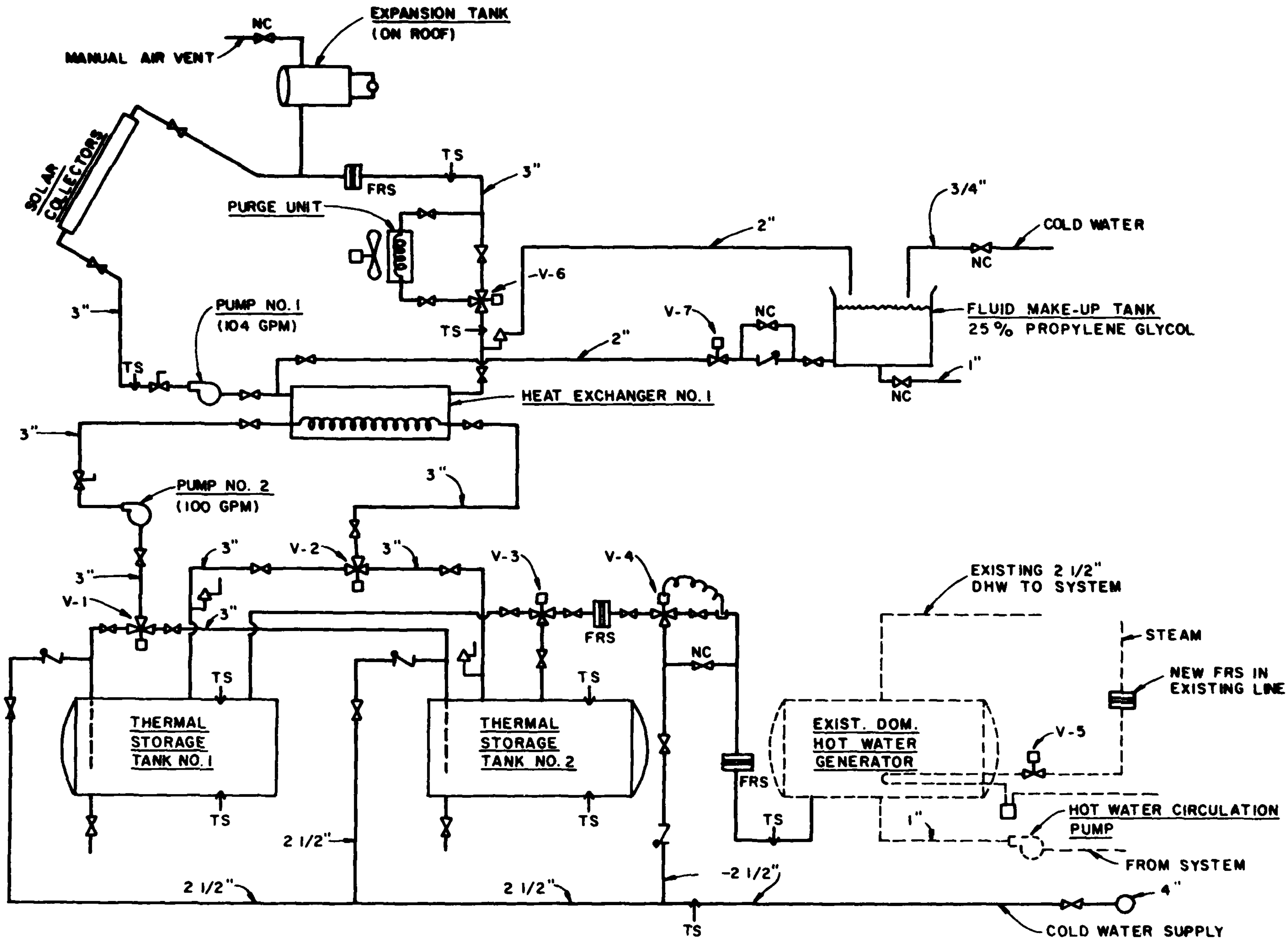


Figure 3. Schematic of solar-assisted DHW system for EM Barracks Building at Fort Hood.

3 SOLAR MONITORING EQUIPMENT AND TECHNIQUE

Except for the EM Barracks Building at Fort Hood, all of the buildings were monitored with computer-based equipment linked to a monitoring network. Because the solar/DHW system at the EM Barracks Building at Fort Hood is simple to operate, the monitoring at that site was done with BTU-Meters.

Monitoring Network

Since three of the solar systems provided both solar space heating and solar cooling, a monitoring network was established to permit a thorough performance evaluation of sophisticated HVAC systems. CERL determined that the following quantities were needed to evaluate the performance of these systems:

- Monthly energy and fuel savings attributable to the solar portion of the system

- The percentage of the heating and cooling loads supplied by the solar portion of the system

- The energy output and efficiency of the solar collector array

- Thermal losses from the solar storage tank

- The average coefficient of performance (COP) of the solar-powered cooling system (absorption chiller).

- Hourly values for the temperatures and flow rates in the piping. For example, to determine if the system provides direct solar heating when the solar storage tank has energy available for this purpose, the average tank temperature for each hour is examined in relation to the source of heating for that hour.

Figure 4 is a block diagram of the monitoring network developed to meet the monitoring requirements. The following technique was used for monitoring with this network:

1. Microprocessor-based data acquisition systems at each site, operating under the control of an onsite computer program, took measurements automatically and temporarily stored the data on magnetic tapes.

2. When telephone calls were made from CERL to a site, the data acquisition system automatically answered the phone and transmitted data requested by the central receiver.

3. After receiving data from a site, the data were processed and recorded on a nine-track magnetic tape for permanent storage at CERL.

This technique let CERL handle the large volumes of data required for a detailed performance analysis of the solar systems. Although the site system could store up to 2 weeks of data, phone calls for data transmission were

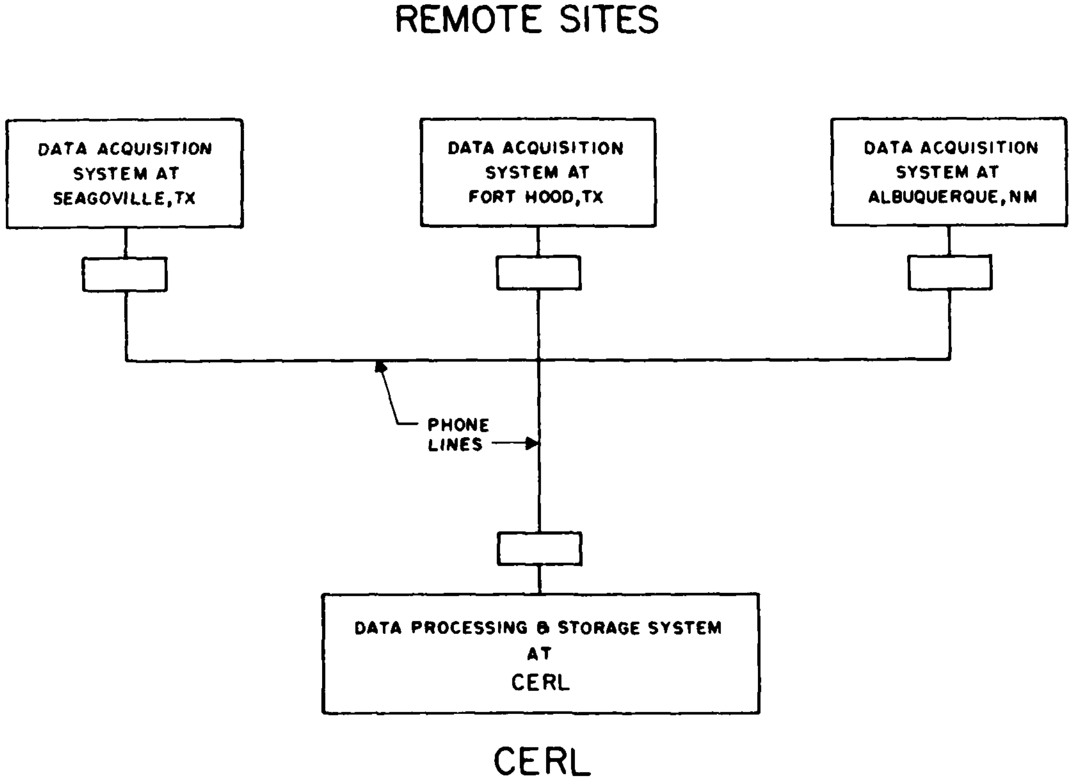


Figure 4. Diagram of monitoring network.

placed roughly once every 2 days. This allowed monitoring equipment malfunctions to be detected very early, minimizing the potential for any data loss. It also made it possible to detect field operating problems quickly. For example, the automatic controls at one site activated the solar cooling system during the winter; this malfunction was detected within 2 days of when it first occurred and reported to the POC at the site for corrective action.

The data acquisition system was programmed to acquire hour-to-hour data. At the end of each hour, the energy sums (e.g., collector heat output) and the average values of the sensor outputs for the previous hour were recorded temporarily on magnetic tape for later transmission to CERL. To acquire these sums and average values, the system took measurements at 1-minute intervals and updated the running totals of the energy sums and average sensor values.

Table 3 lists the energy sums and average sensor values measured for the Albuquerque and Seagoville reserve centers. Table 4 lists the corresponding quantities for the Battalion Headquarters Building at Fort Hood.

Table 3

Measured Quantities for the Albuquerque and Seagoville Buildings

Symbol	Description
T100	Inlet temperature to collector array
TD100	Outlet temperature from collector array
T101	Inlet temperature to solar heat exchanger (from collector array)
TD101	Outlet temperature to solar heat exchanger (to collector array)
T200	Inlet temperature to solar heat exchanger (from solar storage tank)
TD200	Outlet temperature of solar heat exchanger (to solar storage tank)
T201	Inlet temperature of solar storage tank
TD201	Outlet temperature of solar storage tank
T205	Inlet temperature of CW storage tank
TD205	Outlet temperature of CW storage tank
T400	Inlet temperature to space heating load
TD400	Outlet temperature from space heating load
T401	Inlet temperature to condenser of reciprocating chiller
TD401	Outlet temperature of condenser of reciprocating chiller
T402	Inlet to auxiliary heat exchanger (provides connection to DHW boiler)
TD402	Outlet of auxiliary heat exchanger
T500	Inlet temperature of space cooling load
TD500	Outlet temperature from space cooling load
T501	Inlet temperature to evaporator of reciprocating chiller
TD501	Outlet temperature from evaporator of reciprocating chiller
T502	Inlet temperature to evaporator of absorption chiller
TD502	Outlet temperature to evaporator of absorption chiller
T503	Inlet temperature to generator of absorption chiller
TD503	Outlet temperature from generator of absorption chiller
T504	Inlet temperature to condenser of absorption chiller
TD504	Oulet temperature from condenser of absorption chiller
T001	Outside air temperature
T202-204	Temperature at three levels in solar storage tank
T206-208	Temperature at three levels in CW storage tank
W501	Flow through evaporator of reciprocating chiller
W100	Flow through collector array
W200	Flow from solar storage tank to solar heat exchanger
W205	Flow through CW storage tank
W400	Flow through space heating load
W402	Flow through auxiliary heat exchanger
W500	Flow through space cooling load
W504	Flow of condensing water through absorption chiller
EP101	Electrical power for solar collector pump
EP200	Electrical power for solar storage tank pump
EP400	Electrical power for heating/conditioning pump
EP401	Electrical power for reciprocating chiller
EP402	Electrical power for one pump at auxiliary heat exchanger
EP402A	Electrical power for other pump at auxiliary heat exchanger
EP500	Electrical power for chilled water pump
EP501	Electrical power for cooling tower pump
EP504	Electrical power for condensing water pump of absorption chiller
EP600	Total electrical power to the building
I001	Solar flux in the plane of the solar collectors
Q_2	Energy output of solar collectors
Q_3	Energy input of solar heat exchanger
Q_4	Energy input to generator of absorption chiller
Q_5	Energy output of condenser of absorption chiller
Q_6	Energy input to evaporator of absorption chiller
Q_7	Energy input to evaporator of reciprocating chiller
Q_8	Energy output of condenser of reciprocating chiller
Q_9	Energy provided for direct solar heating
Q_{10}	Energy provided for space heating load
Q_{11}	Energy removed to provide space cooling
Q_{12}	Energy input/output of auxiliary heat exchanger

Table 4

Measured Quantities for the Battalion Headquarters Building at Fort Hood

Symbol	Description
T100	Temperature at inlet to solar collector array
TD100	Temperature at outlet of solar collector array
T101	Temperature at inlet of solar heat exchanger
T200	Temperature at inlet of solar heat exchanger (from solar storage tank)
TD200	Temperature at outlet of solar heat exchanger (to solar storage tank)
T201	Temperature at inlet of solar storage tank (from solar heat exchanger)
T210	Temperature near the top of solar storage tank
T211	Temperature near the bottom of solar storage tank
T300	Temperature at the inlet of solar heating coil
TD300	Temperature at the outlet of solar heating coil
T301	Temperature at the inlet of solar storage tank
T305	Temperature at the inlet of conventional heating coil
TD305	Temperature at the outlet of conventional heating coil
T400	Temperature at the inlet of absorption chiller generator
TD400	Temperature at the outlet of absorption chiller generator
T500	Temperature at the inlet of solar cooling coil
TD500	Temperature at the outlet of solar cooling coil
T501	Temperature at the inlet of evaporator of absorption chiller
TD501	Temperature at the outlet of evaporator of absorption chiller
T001	Outside air temperature
T502	Temperature of condensing water for absorption chiller
T505	Temperature at the inlet to conventional cooling coil
TD505	Temperature at the outlet of conventional cooling coil
T510	Temperature near the top of CW storage tank
T511	Temperature near the bottom of CW storage tank
I001	Solar flux in the plane of the solar collectors
W100	Flow through the solar collector array
W200	Flow through the solar storage tank charging loop
W300	Flow through the solar heating coil
W305	Flow through the conventional heating coil
W400	Flow through the generator of the absorption chiller
W500	Flow through the solar cooling coil
W505	Flow through the conventional cooling coil
C10D	Contact closure for collector pump
C101	Contact closure for heat purge fan
C200	Contact closure for solar tank charging pump
C300	Contact closure for solar heating coil pump
C400	Contact closure for absorption chiller generator pump
C500	Contact closure for solar chilled water pump
C502	Contact closure for cooling tower fan
C402	Contact closure for real-time chiller pump operation
Q_1	Collector energy output
Q_2	Heat purged by heat purge unit from solar collectors
Q_3	Energy output of solar heat exchanger (to storage tank)
Q_4	Space heating provided by solar
Q_5	Space heating provided by conventional backup
Q_6	Space cooling provided by solar
Q_7	Space cooling provided by conventional backup
Q_8	Energy input to generator of absorption chiller
Q_9	Energy removed by evaporator of absorption chiller

Sensors

Four types of sensors were used during this study. For drawing notations, each type was assigned a letter code followed by a three-digit number:

- Temperature sensors -- Txxx
- Flow sensors -- Wxxx
- Electric power sensors -- EPxxx
- Solar radiation -- Ixxx.

All temperature sensors were precision platinum resistance probes specified to be accurate to within 0.1°C. Electric power was measured with Watt transducers in conjunction with current transformers. All solar radiation measurements were conducted with precision thermopile units calibrated by the manufacturer.

Different flow sensors were used at each site:

1. Albuquerque: venturi flow sensor with differential pressure transducers.

2. Seagoville: insertable turbine probe.

3. Fort Hood: averaging pitot-tube ("Annubar") with differential pressure transducer.

Figure 5 is a schematic diagram of the location of the sensors for the Albuquerque and Seagoville reserve centers. Figure 6 shows the sensor placement for the Battalion Headquarters Building at Fort Hood.

BTU-Meters at the EM Barracks Building

Since the solar system at the EM Barracks Building is a rather simple design, CERL decided that detailed, hour-by-hour data were not needed to evaluate the system's performance. Thus, this system was monitored with BTU-Meters. A BTU-Meter is a simple device which calculates and totals thermal energy transfer. It is similar to the kilowatt-hour meter used by utility companies to measure electrical energy consumption. The appendix gives a more detailed description of a BTU-Meter.

The monitoring technique used with these meters was straightforward: onsite personnel logged meter readings periodically and mailed the readings to CERL for processing.

Figure 7 shows the location of the BTU-Meters on a schematic diagram of the EM Barracks Building's solar system. The meter registered the following quantities:

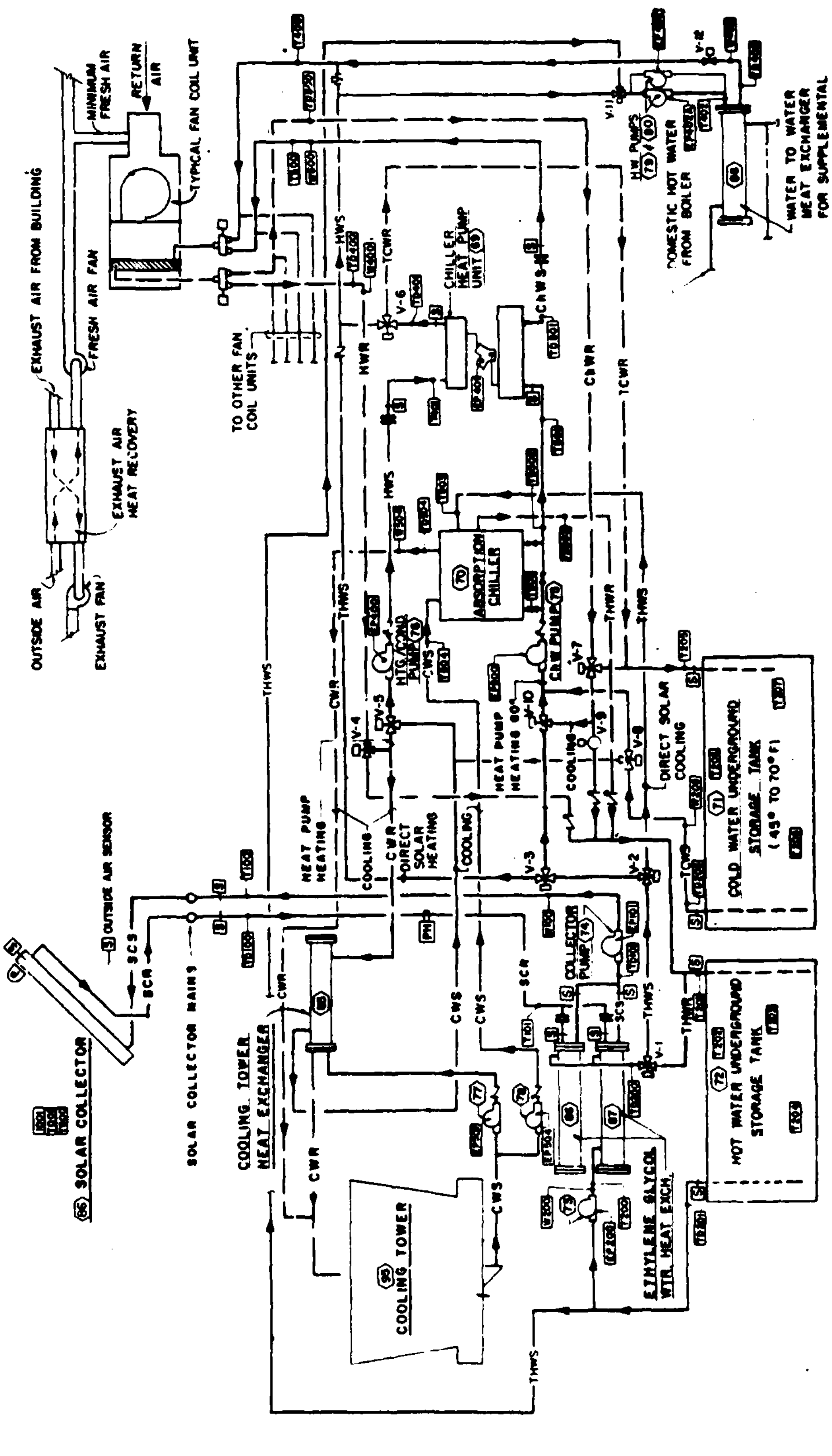
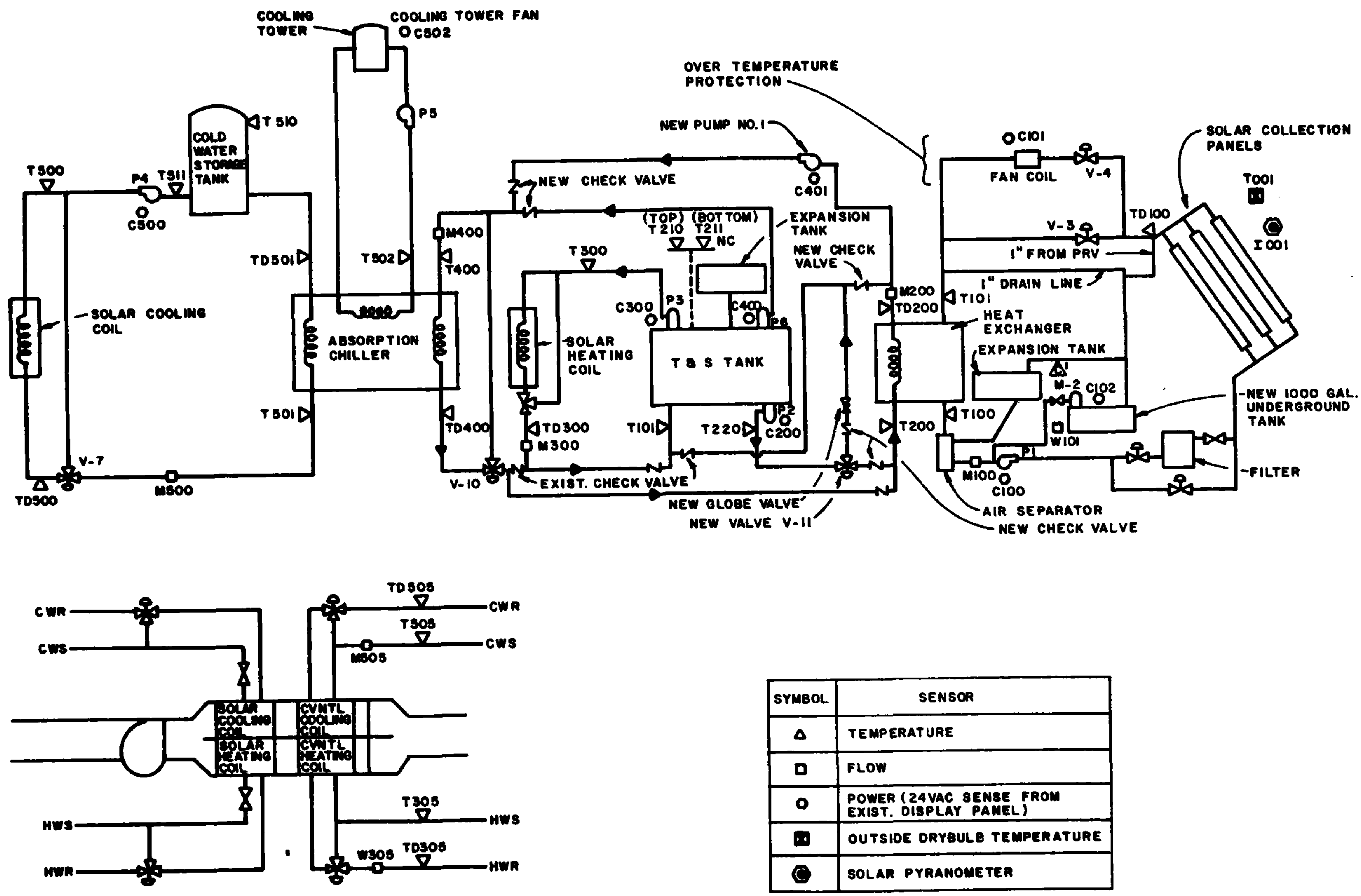


Figure 5. Location of monitoring sensors for Albuquerque and Seagoville buildings.



SYMBOL	SENSOR
△	TEMPERATURE
□	FLOW
○	POWER (24VAC SENSE FROM EXIST. DISPLAY PANEL)
▣	OUTSIDE DRYBULB TEMPERATURE
⬡	SOLAR PYRANOMETER

Figure 6. Location of monitoring sensors for Battalion Headquarters Building at Fort Hood.

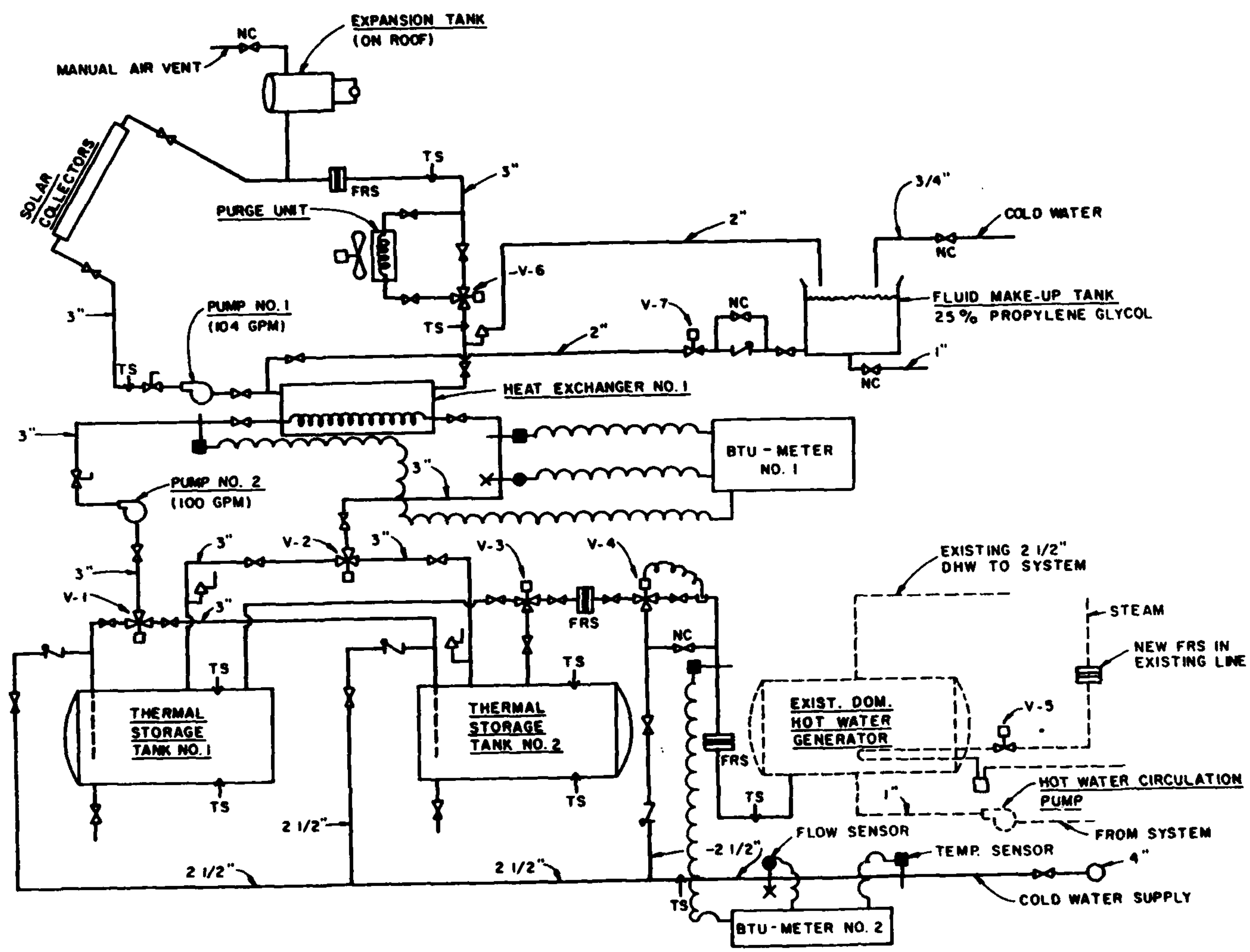


Figure 7. Location of BTU-Meters for EM Barracks Building at Fort Hood.

- The heat output of the solar collectors.

- The DHW heating provided by the solar components.

- The volume of DHW used by the building.

Although weather data like solar radiation and outside air temperature are useful for evaluating BTU-Meter readings, separate weather sensors were not installed at this building because weather sensors were already in place on the Battalion Headquarters Building at this same site.

4 RESULTS FOR THE ALBUQUERQUE RESERVE CENTER

Data Quality Background

To correctly evaluate data, the factors which influence the behavior of the data must be considered. For the analysis of the monitoring data, two factors influenced data behavior:

1. The operating conditions of the HVAC system (e.g., a component operating under manual control for some reason).

2. The status of the monitoring equipment (e.g., a sensor malfunction).

As an example of the first factor, assume the monitoring data reveal that the collector pump operated 24 hours a day for several months at one site. Although this would normally indicate a controls problem, the continuous operation of the pump is actually the result of an intentional action by the operator to purge excessive heat from the system. This excess heat is due to the absence of a significant load: the absorption chiller is not working because it had been severely damaged the previous year. In this case, it is necessary to know the condition of the collection pumps to correctly interpret the data behavior.

As an example of the second factor, assume the initial data from one site indicate that no flow occurs through the solar collectors, even on sunny days. However, an examination of the electric power sensor for the corresponding pump and the values for the corresponding temperature sensors shows that flow is occurring. This indication of a malfunctioning flow sensor in the early data is later confirmed by an onsite inspection and the unit is repaired. Hence, the value from that flow sensor during the initial data monitoring must be ignored.

Overview of the Albuquerque Data

This site was monitored from November 1980 to March 1982. Data for two heating seasons and one cooling season (roughly corresponding to 16 months) were obtained. Compared to the other sites, the Albuquerque data were easier to interpret and allowed a more precise evaluation of the solar system's performance because:

1. The Albuquerque HVAC system experienced fewer operating problems than the other sites.

2. The monitoring equipment performed very well, providing highly accurate and essentially complete data throughout the monitoring interval.

The accuracy of the Albuquerque monitoring equipment was checked as follows:

- The temperature sensors were checked and found to be accurate to within 0.1°C.

• The pyranometer was checked against a second calibrated unit and the outputs were found to agree within 2 percent.

• A check of the energy balance across the solar heat exchanger indicated agreement to within 5 percent.

• The electricity consumption reading for the total building was compared against the electrical usage reported by the utility company for the same time interval. The two values agreed to within 10 percent.

In short, all of the Albuquerque tests indicated that the monitoring data could be used with confidence to evaluate the performance of the HVAC system. During the first 2 months of monitoring, two flow sensors malfunctioned, but were quickly repaired. Data from these sensors did not affect the most important quantities for the performance evaluation.

Monthly Summary of Data

Table 5 gives a monthly summary of the data obtained at the Albuquerque building. The table lists the number of days for each month that data were collected. To evaluate data when portions are absent for some intervals, it is common practice to replace the missing value with mean daily averages. This was done for the Albuquerque data analysis described in the remainder of this chapter. However, these averages produced only minor corrections to the results since the Albuquerque data were essentially complete.

Table 5 also lists the monthly parameters used to describe the performance of the solar components:

• Weather conditions (average outside air temperature and the incident solar energy for the month)

• Average temperature of the solar storage tank

• Average "on-time" of the collector pump (hours per day) and the electrical consumption of the pump (megawatt-hours)

• The energy output of the solar collectors (1 MBtu = 10^6 Btu).

The table also lists the values for the DHW heating by solar, the space heating performance, and the space cooling performance.

In the remainder of this chapter, the data will be evaluated as follows:

• DHW and space heating performance

• Space cooling performance

• Solar collector performance

• Solar storage tank losses

Table 5

Monthly Summary of Data from Albuquerque

Month	Amount of Data (days)	Air Temperature (°F)	Incident Solar Energy (kBtu/sq ft)	Solar Tank Temperature (°F)	SOLAR COLLECTORS Pump on (hours)	Pump Electric (MWh)	Energy Collected (MBtu)
11/80	14	37	22.0	126	5.3	0.65	55.5
12/80	30	41	50.5	127	6.4	1.85	124.5
01/81	31	39	48.5	132	6.7	1.86	109.0
02/81	28	44	53.7	141	7.2	1.80	156.9
03/81	31	46	55.7	151	6.4	1.93	147.0
04/81	30	61	63.9	158	18.8	5.81	198.4
05/81	31	65	68.4	149	23.5	6.51	211.3
06/81	30	79	69.8	162	23.6	7.15	211.1
07/81	31	80	68.2	162	23.4	6.93	215.1
08/81	27	76	58.7	163	23.3	6.76	199.7
09/81	28	70	55.4	155	21.8	5.74	187.7
10/81	31	56	55.4	160	11.5	4.46	142.7
11/81	27	48	45.7	155	5.9	1.49	112.9
12/81	25	40	41.6	122	7.2	2.08	132.8
01/82	27	37	38.3	111	6.0	2.00	121.8
02/82	25	38	33.2	123	6.4	2.01	90.2

Table 5 (Cont'd)

Month	DHW Heat From Solar (MBtu)	Total Heat (MBtu)	SPACE HEATING Solar Heat (MBtu)	Solar Fraction (%)	Total Cooling (MBtu)	SPACE COOLING Solar Cooling (MBtu)	ABSORPTION CHILLER Solar Fraction (%)	On Time (Hours)	Average COP
11/80	1.08	70.6	52.5	74	1.9	0.0	0	0	0
12/80	3.83	122.4	87.4	71	0.0	0.0	0	0	0
01/81	2.03	165.4	95.9	58	0.0	0.0	0	0	0
02/81	6.85	104.6	77.4	74	0.0	0.0	0	0	0
03/81	8.96	76.4	64.9	85	0.0	0.0	0	0	0
04/81	6.51	12.9	11.1	86	46.2	0.0	0	0	0
05/81	6.34	0.0	0.0	100	81.5	0.0	0	0	0
06/81	4.64	0.0	0.0	100	137.1	0.0	0	0	0
07/81	7.68	0.0	0.0	100	155.5	0.0	0	0	0
08/81	5.89	0.0	0.0	100	134.5	0.0	0	0	0
09/81	5.65	0.0	0.0	100	110.9	0.0	0	0	0
10/81	9.64	30.5	29.5	97	28.5	0.0	0	0	0
11/81	8.18	77.0	72.1	94	5.6	0.0	0	0	0
12/81	0.06	123.9	106.1	86	0.0	0.0	0	0	0
01/82	0.41	146.2	92.5	63	0.0	0.0	0	0	0
02/82	1.23	130.1	60.1	46	0.0	0.0	0	0	0

*The absorption chiller was not operated because of prior damage; hence no solar cooling was supplied.

- Energy savings

- Field experience ("lessons learned").

DHW and Space Heating Performance

Table 6 gives the results of the data analysis of two heating seasons at Albuquerque. The fraction of the space heating provided directly by the solar components was 72 percent for the first heating season and 73 percent for the second heating season. The measured values of the solar fraction are less than the design value of 100 percent. When the total heating load is compared with the design heating load, the actual load is 72 percent greater for the first heating season and 75 percent greater for the second heating season. Because of the higher space heating load, the actual savings in space heating provided by the solar components are 24 percent greater than predicted by the design calculations. The higher space heating load is attributed to a smaller electrical energy consumption (e.g., for lighting, which would have added heat to the space) than expected by the design calculations.

The solar collector array was observed to have controls problems during the winter heating season. The collector pumps were observed to operate intermittently at night during December and January. The data indicate this erratic night operation was responsible for losing about 25 percent of the energy collected during the coldest winter months. It was not possible to study this loss mechanism during the summer because the pumps operated continuously to expel heat from the system.

Table 6 also shows that the total space heating load and solar fraction varied very little from the first heating season to the second. As described in the last section of this chapter (Field Experience), the heating system was operated manually during the first heating season because the HVAC controls failed. But the hour-by-hour data indicated that manual operation should have had little effect on the system performance. The reproducibility of the data supports that contention.

The annual DHW heating provided by solar was measured at 72 MBtu. This quantity was difficult to measure because of the system's operating method. The DHW heating was measured to be only 11 percent of the total heat demand of the building.

One unusual feature of this design was the inclusion of several modes of space heating to supplement the heating provided directly by the solar portion of the system. Although it is normal practice to include one backup mode of heating, this design included several heating modes involving the use of the reciprocating chiller in addition to the normal backup heating provided by a boiler. Since the inclusion of these additional heating modes added to the complexity of the system, it is of interest to evaluate the benefits provided.

As noted in the description of the system at this site, the reciprocating chiller was to operate as a "heat pump," with the condenser water circulated to the fan-coil units for heating. The performance of the heat pump heating modes is not included in Table 6 because the system did not operate in these modes so they provided no heat savings during either heating season.

Table 6

Analysis Results for Space Heating at Albuquerque

Quantity	Measured Values 80-81	Measured Values 81-82	Design Values	Measured Value ÷ Design Value
Total heating load (MBtu)	580	598	342.1	1.72
Space heating from solar (MBtu)	423	437	342.1	1.26
Solar fraction	72%	73%	100%	0.73

At first glance, it might appear that this is what should be expected according to the design calculations. That is, all space heating would be supplied by direct solar heating without the aid of the heat pump. Thus, the system would not be expected to operate in the heat pump heating modes during average winter conditions. However, the actual space heating load was higher than expected and the heat pump heating modes should have saved some energy. They did not save any energy because the system did not function in these modes during either heating season.

The experience with the system leads to the conclusion that the heat pump heating mode is not needed for this system for the following reasons:

1. Even though the heating load over the winter was higher than originally estimated in the design, it could have been met almost entirely (about 95 percent) by direct solar heating. This could be achieved by eliminating the excessive solar system losses (about 25 percent of the collected energy).

2. One planned operating mode involved the use of the heat pump to move heat (from lights and people) in the interior zones to the exterior zones when they required heating. However, due in part to reduced interior lighting consumption, simultaneous heating and cooling was never needed. Hence, the heat pump would not have functioned in this mode even when heat could not be provided directly by the solar components.

Even if there was heat in the interior available for redistribution by the heat pump, each time the operator attempted to run the chiller as a heat pump in this system configuration, the chiller "kicked off" due to high condenser head pressure. This was because the water entering the evaporator was too hot (that is, outside the operating range of the machine) and the chiller would not run long enough to cool the water to the temperature required for successful operation. Because of the failure of the system to operate in these heating modes, the operator was forced to manually operate the controls to allow backup heating by the boiler when the solar components were unable to provide direct solar heating.

Overall, the experience shows that the additional expense and added complexity of the system associated with the heat pump heating modes is not needed nor is it justified by the performance for this application.

Space Cooling Performance

Table 7 summarizes the analysis results for the 1981 cooling season. The building's total cooling load was 13 percent lower than predicted by the design calculations. The lower value for the space cooling is attributed to a lower electrical energy consumption (e.g., for lighting) than expected by the design calculations.

The absorption chiller did not function because it was damaged before the monitoring began. Consequently, the solar system saved no energy during the cooling season.

The performance of the reciprocating chiller was measured as follows:

1. The electrical consumption of the reciprocating chiller was 20 times higher than expected by the design calculations, since it provided all of the cooling.

2. The average COP value was 3.3, 13 percent lower than the value of 3.8 used in the design calculations.

Since the reciprocating chiller features several stages of unloading cylinders to match the load conditions, the chiller's instantaneous COP would be expected to vary according to the load conditions. However, the data revealed that the chiller operated an average of 10 hours a day from May through September and had an instantaneous COP of 3.3 most of the time.

The HVAC system design at this site included several automatic control valves and piping interconnections to permit the reciprocating chiller to function as a heat pump during the winter. Since these valves may permit fluid to leak between the chilled water and hot fluid piping (e.g., from the solar storage tank to the chiller evaporator), serious thermal losses are possible. This possibility was examined by comparing the cooling output at the chiller's evaporator with the cooling delivered to the space cooling load. The thermal losses from the chiller were found to correspond to about 25 percent of the chiller output.

Background on Solar Collector Efficiency

Before analyzing the solar collector performance, background information on solar collector efficiency will be presented. The standard definition of the collector efficiency is given by

$$\eta = \frac{Q_{out}}{I} \qquad \text{[Eq 1]}$$

Table 7

Analysis Results for Space Cooling at Albuquerque

Quantity	Measured Value	Design Value	Measured Value ÷ Design Value
Total cooling load (MBtu)	701	807	0.87
Space cooling from solar (MBtu)	0	791	0
Solar fraction	0	98%	0
Electricity used by reciprocating chiller (MWh)	74.8	3.76	19.9
Average COP of reciprocating chiller	3.31	3.8	0.87

where:

Q_{out} = the energy output of the collector array

I = the solar energy incident upon the array.

The efficiency of solar collectors depends on the operating conditions. It has been established that the performance of solar collectors can be characterized by the collector efficiency measured as a function of the fluid parameter, F, defined by:

$$F = T_f - \frac{T_a}{i} \qquad \text{[Eq 2]}$$

where:

i = the solar flux intensity in the plane of the collectors

T_f = the collector fluid temperature

T_a = the site ambient temperature

As illustrated in Figure 8, the efficiency of flat-plate collectors as a function of F can be approximated as a straight line. That is, the efficiency decreases linearly with increasing fluid parameter.

The collector efficiency behavior can be understood by separating the energy loss mechanisms by the collector into two parts: (1) optical losses which are essentially independent of the value of F and (2) thermal losses which increase proportionately with F. These two loss mechanisms are also illustrated in Figure 8.

Eq 2 shows that the fluid parameter is a measure of the difference in temperature between the collector and its surroundings, with the solar flux intensity included as a scaling parameter. Hence, for a given solar flux intensity and ambient temperature, higher values of the operating temperature of the collector correspond to higher values of the fluid parameter F.

By knowing the expected range for the operating temperature of a solar system, one can calculate rough values for the operating range of F. For example, normal values for the solar flux intensity can be taken as 250 Btu/hr/sq ft and the ambient temperature in the summer can be assumed to be roughly 90°F. Then, a solar pool heating system would have collectors operating at approximately 90°F and the fluid parameter value would be roughly zero. For a DHW system with collectors at 120°F, the fluid parameter value would be 0.12. For a solar cooling system, the collectors would be operating at about 200°F and the fluid parameter value would be 0.44.

Since the collector efficiency varies with F, it is important to select a collector based on its efficiency in the operating range expected for the application. Figure 9 illustrates the marked difference in efficiency of two different types of collectors. The collector labeled type 1 in the drawing has a high efficiency at low F values but its efficiency drops rapidly with increasing F. This type of collector would be appropriate for a low-temperature application, such as a solar pool heating application, but would be totally unsuitable for a high temperature application (such as solar cooling).

By contrast, the collector labeled type 2 in the drawing has a much lower efficiency than type 1 at low values of F and it would be markedly inferior to type 1 for solar pool heating. However, the efficiency of type 2 decreases much more slowly with increasing F. By examining its efficiency values at high values of F, it is quite clear that this collector provides reasonable efficiency values in the operating range expected for solar cooling applications and would be suitable for this type of application. This example illustrates the need to carefully select a collector based on its efficiency values in the operating range of F for the particular application.

Solar Collector Performance

The solar collector performance was evaluated by examining:

1. The instantaneous collector efficiency as defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Inc., Standard 93-77.[4]

2. The average collector efficiency on a monthly and seasonal basis.

[4] Methods of Testing to Determine the Thermal Performance of Solar Collectors, Standard 93-77 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE], Inc., 1977).

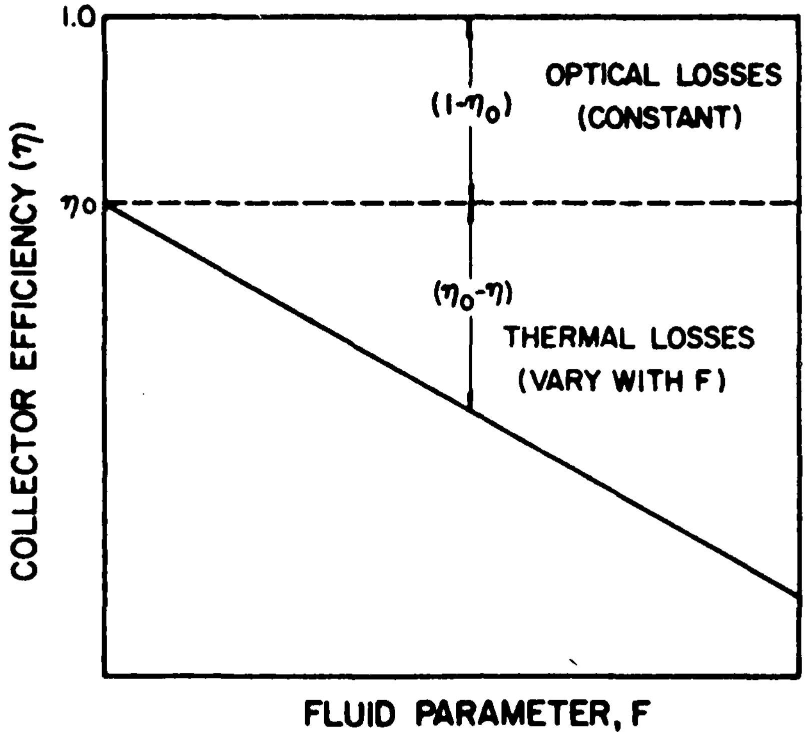


Figure 8. Typical behavior of collector efficiency for flat-plate solar collectors.

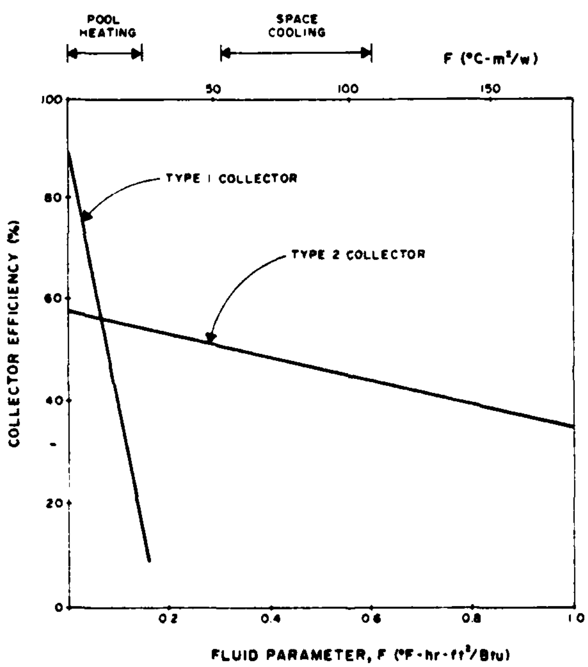


Figure 9. Marked difference in behavior of collector efficiency for two types of commercially available collectors.

These two quantities provide different information about the solar performance because of:

1. The instantaneous collector efficiency depends primarily on the basic characteristics of the solar collector array; it is virtually independent of the behavior of the other parts of the HVAC system and is independent of the weather conditions.

2. By contrast, the average collector efficiency depends strongly on the weather conditions and the operation of the other parts of the HVAC system.

Instantaneous Collector Efficiency

Table 8 compares the measured values of the instantaneous collector efficiency with the corresponding values for a single collector subjected to an ASHRAE 93-77 test at a testing laboratory. The test data for the single collector are from the manufacturer's specifications for the collector model installed at this site. The single-collector test results were confirmed independently by a test laboratory when questions arose concerning the suitability of the collectors installed by the contractor at Albuquerque. The test was then performed on several collectors taken from the Albuquerque site. The test results were sent to the Fort Worth District by the test laboratory.

The table shows excellent agreement between the measured array efficiency and the test data for a single collector. Of course, the test data for the single collector met the requirements of the construction specifications. The monitoring data show that the entire array performed as would be expected from the manufacturer's test data.

Average Collector Efficiency

Table 9 shows the analysis results for the collector performance during the two heating seasons. The table compares the measured values of the average collector efficiency with those given in the design calculations by the A/E firm. Since the collector efficiency depends on the operating parameters (outside air temperature, incident solar energy, and solar tank temperature), the measured values are listed side by side with the design values. This allows the efficiency values and the operating parameters to be compared. This comparison determines the efficiency values.

The table shows that the measured efficiency values for each winter month are about the same as the design values. Indeed, if an average is taken over a heating season (five winter months), the average efficiency from the design is 26.7 percent, whereas the average measured efficiency is 25.5 percent. Although the comparison of the two efficiency values indicates excellent agreement, the indication is highly misleading. This is because one operating parameter, the average tank temperature, is markedly different. The table shows that the design calculations expected an average efficiency of 26.7 percent at tank temperatures much higher (roughly 70°F higher) than those that actually occurred.

Table 8

Comparison of the Measured Collector Array Efficiency With the Manufacturer's Test Data for a Single Collector

Date	Hour	Fluid Parameter (°F-hr-ft²/Btu)	Measured Array Efficiency	Efficiency From Test Data
11/07/80	11:00	0.471	28%	29%
	12:00	0.495	26%	27%
	13:00	0.555	19%	20%
12/09/80	10:00	0.346	36%	42%
	11:00	0.333	40%	44%
	12:00	0.353	40%	42%
	13:00	0.406	36%	36%
	14:00	0.509	29%	25%
12/20/80	10:00	0.349	37%	42%
	11:00	0.339	41%	43%
	12:00	0.338	41%	43%
	13:00	0.382	39%	39%
01/27/81	10:00	0.418	31%	35%
	11:00	0.384	37%	38%
	12:00	0.378	38%	39%
	13:00	0.412	36%	36%
	14:00	0.512	28%	25%
02/22/81	10:00	0.383	36%	39%
	11:00	0.360	40%	41%
	12:00	0.358	41%	41%
	13:00	0.383	39%	39%
	14:00	0.440	34%	33%
03/13/81	10:00	0.437	33%	33%
	11:00	0.359	42%	41%
	12:00	0.358	44%	41%
	13:00	0.398	42%	37%
01/07/82	11:00	0.292	47%	48%
	12:00	0.431	35%	34%
	13:00	0.345	44%	42%
	14:00	0.354	38%	41%
02/28/82	11:00	0.321	42%	45%
	12:00	0.325	43%	44%
	13:00	0.350	42%	42%
	14:00	0.409	37%	36%

Table 9

Monthly Summary of Data for Solar Collector Performance at Albuquerque

Month	Average Outside Air Temperature		Incident Solar		Average Tank Temperature		Average Collector Efficiency	
	Measured Value (°F)	Design Value (°F)	Measured Value (kBtu/sq ft)	Design Value (kBtu/sq ft)	Measured Value (°F)	Design Value (°F)	Measured Value (%)	Design Value (%)
12/80	41	35	52.2	39.0	127	208	24.6	24.5
01/81	39	34	48.5	42.0	132	185	22.5	30.9
02/81	44	39	53.7	47.1	141	230	29.2	23.2
03/81	46	45	55.7	57.6	151	231	26.4	25.8
11/81	48	44	50.8	44.3	155	209	24.7	29.8
12/81	40	35	51.6	39.0	122	208	31.9	24.5
01/82	37	34	44.0	42.0	111	185	31.8	30.9
02/82	38	39	37.2	47.1	123	230	27.2	23.3

The efficiency values at the higher tank temperatures are important because:

1. This system was sized to provide space cooling. Most of the energy and fuel cost savings were to be provided by solar cooling. The design calculations show that the absorption chiller was to begin operating in February and provide solar cooling until the middle of December.

2. The design calculations indicated that the average tank temperatures would be 230°F in February and remain above 200°F through December, when the average temperature would be 208°F.

3. An absorption chiller requires such high temperatures to provide space cooling at a reasonable capacity and coefficient of performance.

The interior performance at high tank temperatures revealed by the monitoring data indicates that the amount of solar cooling would be less than expected from the design calculations. Hence, the energy and fuel cost savings provided by the solar components would be substantially reduced.

To indicate the collector performance at high tank temperatures predicted by the monitoring data, a calculation was performed on a typical sunny day in January. This calculation was based on the fact that the collector efficiency followed the performance curve provided by the manufacturer (Table 8). For the sunny day in January, the tank temperature was 135°F and the instantaneous efficiency averaged 50 percent. If these values are shifted to the average tank temperature of 184°F, the instantaneous efficiency would average only 22 percent. A similar calculation shows that the efficiency values for a partly cloudy day would show an even greater decrease in efficiency with higher tank temperatures.

The overall results of the collector performance analysis indicate that the solar system would provide roughly half of the energy for solar cooling expected by the design calculations. Thus, the collector's actual performance was inferior to that expected by the design, even though the measured performance (for the instantaneous collector efficiency) equaled the performance required by the construction specifications. This is a result of the following:

1. The collector efficiency performance specification was based on the fluid parameters values of 0.15 and 0.30°F-ft^2-hr/Btu (corresponding to moderate tank temperatures).

2. However, the design calculations were based on the solar system operating above the fluid parameter value of 0.3°F-ft^2-hr/Btu (which corresponds to high tank temperatures) virtually the entire year.

Figure 10 compares the actual efficiency of the collectors installed at the site and the efficiency expected by the design calculations. The figure demonstrates the disparity between the interval used for the construction specifications and the operating interval indicated by the design calculations. Hence, the construction specifications did not require collectors with a good performance at high temperatures, even though a good performance at high temperatures was assumed in the design calculations.

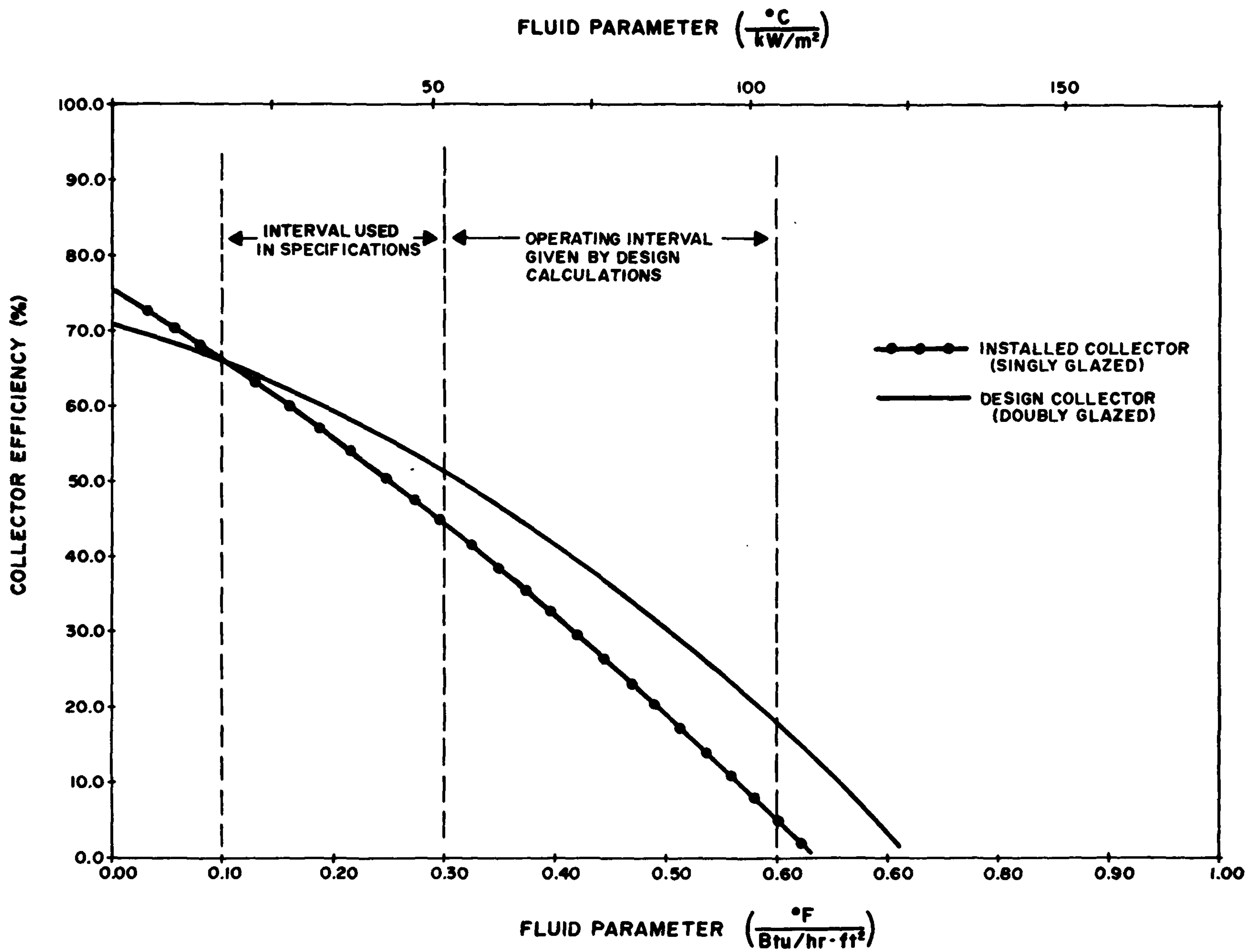


Figure 10. Comparison of collector efficiency performance expected by the design calculations with that provided by the collectors actually installed.

Figure 11 shows the Department of Energy's guidelines for the operating interval of solar collectors for various types of systems.[5] These guidelines can be used when detailed computer simulations are not performed during the design. The guidelines show that the operating interval for the collector performance specification should be 0.3 to 0.6 for solar cooling systems. For the Albuquerque design, the detailed computer calculations indicated that the operating interval was between 0.3 and 0.6.

Solar Storage Tank Losses

The thermal losses from the solar storage tank were carefully studied. The study revealed that the tank thermal losses amounted to 0.17 MBtu per day under typical winter operating conditions. This corresponds to a loss of roughly 2 percent of the tank's thermal capacity on an average winter day. The loss per month would then be about 5 MBtu and represent a loss of 5 percent of the energy collected during the winter months. Overall, the study showed that the tank is well-insulated and its performance is excellent. The tank meets the rather stringent Sheet Metal and Air Conditioning Contractor's National Association (SMACNA) standard for thermal storage tanks.[6]

Energy Savings at Albuquerque

The heating provided by the solar energy system at this building saved 660 MBtu of heat from the natural gas boiler. The annual cost savings for the natural gas consumption is then $2750. However, the additional electrical energy consumption by the solar collection pump during the wintertime amounted to 8.9 MWh or $523. When this is subtracted from the natural gas savings, the net savings for heating is roughly $2225 per year.

During the summer, no cooling was provided by the solar portion of the system. During this time, the added electrical consumption associated with the solar collection pumps was 83 MWh, which corresponds to an added cost of $4878. Hence, the addition of solar components to the building resulted in higher fuel costs (an extra $2750) than would have been consumed by using a conventional HVAC system.

The excessive summer fuel costs were caused because the solar collection pumps had to operate continuously to expel excess heat and avoid over-temperature conditions in the solar collectors. Although this prevented the solar collectors from being severely damaged, it is an inefficient and costly way to eliminate excess heat. Moreover, a building operator must manually operate the system. A heat purge unit, operating under automatic control, would be a more efficient and reliable method of expelling excess heat.

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[5] Introduction to Solar Heating and Cooling Design and Sizing, DOE/CS-0011 (Department of Energy, 1978).

[6] Heating and Air Conditioning Systems Installation Standards for One and Two Family Dwellings and Multifamily Housing Including Solar (Sheet Metal and Air Conditioning Contractor's National Association [SMACNA], 1977).

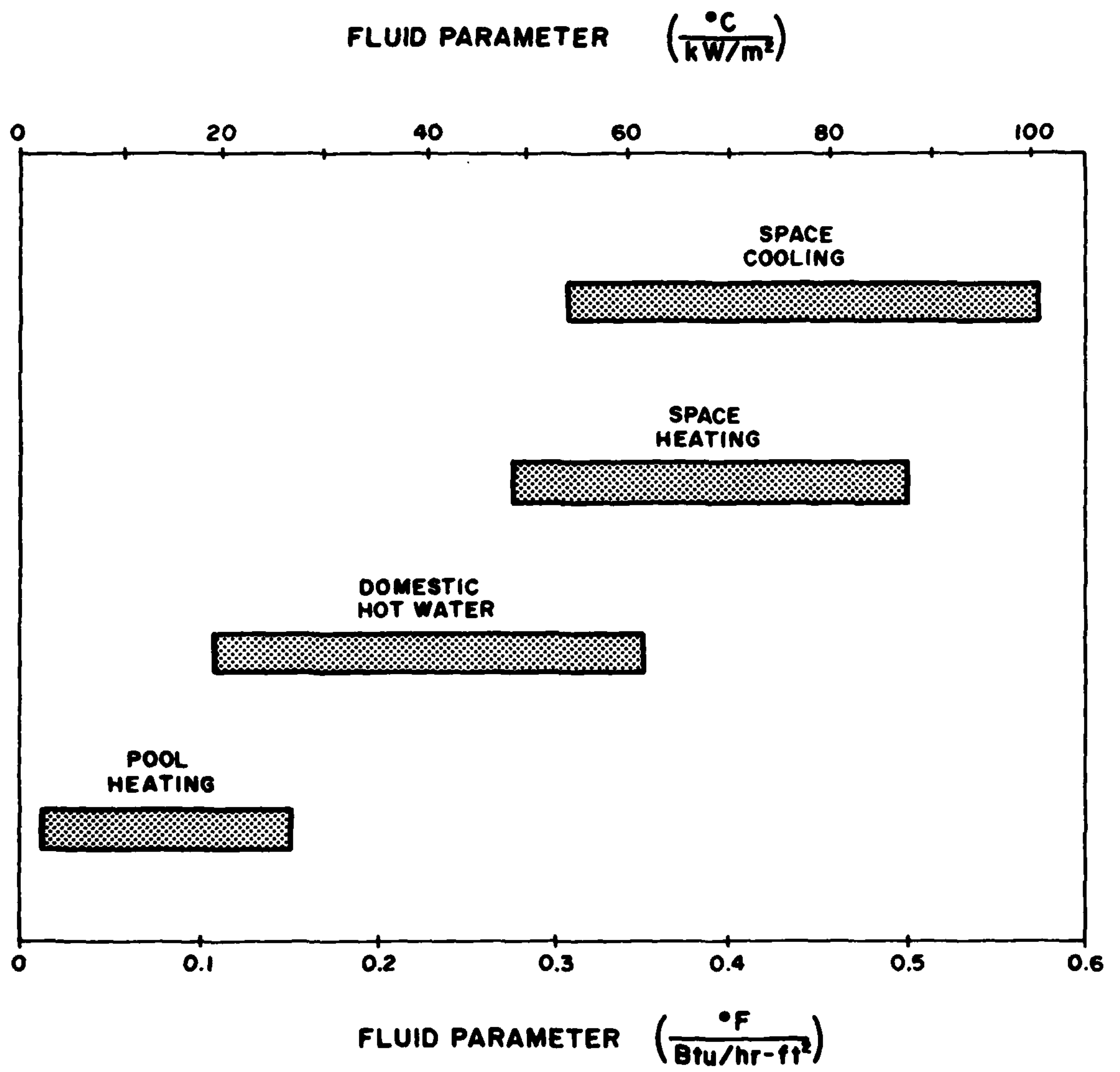


Figure 11. Guidelines for operating range of various solar energy systems.

The magnitude of the excess heat at this site was influenced by the fact that the absorption chiller was not operating. However, even if the absorption chiller had been operated, the data show that there are intermediate seasons (spring and fall) in which excess heat would still have to be eliminated. It is estimated that an additional $1400 of electricity would be expended rejecting this excess heat if the present method were used (manually operating the collector pumps). Moreover, the method depends on having an operator carefully monitoring the system to determine when the excess heat must be expelled. A heat purge unit operating under automatic control must be provided to eliminate this requirement.

It may be argued that the solar system at this site could have been cost effective if the solar cooling system had worked. However, the monitoring data reveal that the reciprocating chiller provided 100 percent of the space cooling and consumed only 75 MWh of electricity at a cost of $4380. Even if the solar system had provided 100 percent of the space cooling, the potential annual cost savings for heating and cooling ($6600) is very small compared to the overall costs of the solar system ($750,000) and the excessive O&M costs ($25,000 per year) of this complex system.

The above assessment of the economic feasibility of this design does not include the high costs of repairing components that were severely damaged at this site (and components at the Seagoville site, which has a similar design, have experienced severe damage). Since this complex system is susceptible to failures, the designer should include failsafe protection features in the design (for example, heat rejection method to prevent overheating of solar collectors) or the design should factor in the high cost of repairing components when failures do occur.

Even if the high costs of repairing damaged equipment are not included in the economic assessment, the monitoring data clearly show that the complex solar system at this site is not economically feasible.

Field Experience

CERL's study uncovered two major operating problems with the Albuquerque system:

1. The automatic controls for the wintertime modes did not function during the first heating season.

2. The absorption chiller did not function during the cooling season.

The first of these problems, the failure of the automatic controls for the wintertime modes, was discovered during a trip to the site to start data collection and transmission. Building occupants complained of being cold despite the moderate November weather. The monitoring equipment revealed that the solar storage tank temperature was 220°F, but that no tank fluid was being delivered to the fan-coil units. The automatic controls unit was attempting to activate one of the waste heat recovery modes, but that mode would not function. Subsequently, CERL worked with the building operator to manually operate the controls and restore heat to the building. The system operated entirely under manual control during the remainder of the first heating season. Hence, the data for the first heating season are for a system operating under manual control. The following two modes were used:

1. The direct solar heating mode

2. A backup mode with the heating by the DHW boiler.

Because of the nature of manual control, the changeover between the two modes was not exactly the same as would be produced by an automatic controls unit. For instance, there were a few occasions in which the system was switched to the backup mode just before a weekend even though the solar system had the capacity to heat the building that weekend. This was not an operator error, but simply a reflection of the need to provide heating for the upcoming weekend when no operator would be on duty and adverse weather conditions might occur.

Although it was important to note the use of manual control when examining the data for indications of proper operation, the data indicated manual control had little effect on important quantities like the amount of heating from solar, the solar fraction, and collector efficiency. Also, only a small difference in performance was found when the system operated under automatic control during the second heating season.

The absorption chiller was severely damaged before the cooling season. This had two major effects on the summertime monitoring data:

1. No cooling was provided by the solar system. All cooling was by the reciprocating chiller installed as a backup unit.

2. The solar collection pumps operated continuously to purge excessive heat from the system and protect it from being damaged by overheating.

The absorption chiller was not repaired until the Spring of 1982, after the monitoring was concluded.

The monitoring data indicated that the solar collection pump operated erratically. When the solar controls were being installed by the construction contractor, the control sensor for the collector was mounted improperly. This was later corrected. However, the control sensor for the solar tank was mounted on piping instead of in the tank. This meant that the sensor did not accurately detect the tank temperature when the pump was not operating.

5 RESULTS FOR THE BATTALION HEADQUARTERS BUILDING AT FORT HOOD

Overview of the Data Collected

Data were collected at this site during the 1980-81 heating season and during the following cooling season (Summer 1981). The data collection effort at this site was less successful than the one at the Albuquerque site. The data are less complete and not as accurate because of the problems discussed in detail in the last section of this chapter (Field Experience). The problems which had a major impact on the data quality were:

1. Equipment problems which caused the loss of data for the first part of the 1980 heating season.

2. Damaged flow sensors and inaccurate temperature sensors affected data accuracy.

3. No solar cooling was provided during the cooling season.

The flow sensors were damaged when they were first valved in by onsite personnel. Some of the data were evaluated by inserting the measured steady-state values and reprocessing the data. A check of this procedure indicated that accuracy was about 15 percent with this technique.

The data accuracy was also apparently affected by temperature errors which exceeded the manufacturer's specifications. The portions of the data known to have anomalous temperature readings were not used in the analysis.

Monthly Summary

Table 10 gives a monthly summary of the data obtained at this site, including the number of days for each month that data were successfully collected. Also listed are:

- Weather conditions (average outside air temperature and the incident solar energy for the month)

- Average temperature of the solar storage tank

- Space heating data (total heating load, amount of heat supplied by the solar components, and the fraction of the heat supplied by solar [1 MBtu = 10^6 Btu])

- Performance data for the solar cooling unit (absorption chiller).

Data for the solar collector performance are discussed in this chapter. These data were evaluated to obtain:

- Space heating performance

- Space cooling performance

Table 10

Monthly Summary of Data from Battalion Headquarters Building at Fort Hood

					SPACE HEATING			ABSORPTION CHILLER		
Month	Amount of Data (days)	Average Outside Air Temperature (°F)	Incident Solar Energy (kBtu/ft^2)	Average Solar Tank Temperature (°F)	Total Heat (MBtu)	Solar Heat (MBtu)	Solar Fraction (%)	Solar Cooling (MBtu)	Average on-time (hrs/days)	Average COP
01/81	18	55	24	143	104	4	4%	0	0	0
02/81	21	55	24	123	191	20	11%	0	0	0
03/81	31	64	45	126	131	38	29%	0	0	0
04/81	30	76	45	139	12	12	100%	0	0	0
05/81	31	78	53	148	11	11	100%	0	0	0
06/81	11	84	16	179	0	0	100%	0	0	0

- Solar collector performance
- Energy savings.

Space Heating Performance

Table 11 summarizes the analysis results for space heating and cooling at this site. The data indicate that the solar system provided 85 MBtu of heat during the monitoring interval. This is 36 percent more than the annual energy savings for space heating predicted by the design. Since there was a possibility of a temperature error in the data, the amount of solar heating was carefully checked by comparing it to the solar collector heat output and the changes in the solar storage tank temperature. This check showed that the value for solar heating was accurate.

The data indicate that the fraction of the space heat provided by solar at this building was only 19 percent, far below the design value of 98 percent. This was caused by the data's indication of a space heating load during the monitoring interval that was 7.2 times larger than annual heating load calculated by the designer. This anomalously large measured value for the space heating load may be inaccurate because of temperature errors of the type diagnosed early during the monitoring for some sensors. Since this was an isolated loop, no direct cross-checks were possible. Nevertheless, the data show that the conventional heating system was on much of the time. For instance, the conventional heating system was on at least 4 hours every day in January and February. Overall, the "on-time" data are consistent with a large heating load at the building.

The solar system design at this site was examined to see if an explanation could be found for such a large space heating load. The design had a multizone air handler, and included an economizer cycle. When the outside air temperature was below 60°F, the economizer cycle operated a damper to introduce outside air. It then attempted to maintain a mixed-air temperature of 55°F to the supply inlet of the fan. A simple calculation indicated that the

Table 11

Analysis Results for Space Heating and Cooling
at the Battalion Headquarters Building at Fort Hood

Quantity	Measured Value (01/81 to 06/81)	Projected Value from the Measured Data	Values From the Design Calculations
Total heating load (MBtu)	450	680	63
Space heating from solar (MBtu)	85	127	62
Solar fraction for space heating	19%	19%	98%
Space cooling from solar (MBtu)	0	0	303
Solar fraction for space cooling	0%	0%	83%

economizer cycle could produce an unusually large space heating load during the winter months and could produce an annual heating load 10 times the annual heating load listed in the design calculations. This calculation is consistent with CERL's observation that the conventional heating system operated almost continuously for long periods during the winter months. If this method of operation is confirmed during a site visit, it is recommended that the mixed-air controls be overridden during the winter months.

In addition to an excessive wintertime space heating load, system controls continued to operate the heating system during the summer, even after the cooling system was started. CERL observed that the heating system controls were completely out of calibration. Hence, the inoperable control components could have contributed, at least in part, to an excessive consumption of space heat.

Space Cooling Performance

The solar system was sized to meet the predominant cooling load at this site. The design calculations indicated that the annual cooling load would be six times larger than the annual heating load. Accordingly, more than 80 percent of the savings by the solar system were to be provided by solar space cooling. However, the monitoring data indicated:

1. The solar cooling components did not operate at the site and provided no energy savings.

2. Solar heating was supplied during the summer, thereby causing the conventional space cooling system to consume additional energy. (An onsite inspection by CERL found a malfunction in the building's pneumatic controls.)

3. The absorption chiller controls malfunctioned.

4. Excessively high temperatures were generated in the solar collectors. The heat purge unit did not operate initially.

These HVAC system problems are discussed in detail later in this chapter under the Field Experience section. As noted there, the equipment problems were reported and corrected. However, a poor space heating and over-temperature conditions in the collectors occurred again later in the cooling season. Subsequently, the heat purge unit was observed to be operating continuously, as if it were manually placed in operation. The monitoring was terminated at this point.

Solar Collector Performance

Table 12 lists the measured values of the instantaneous collector efficiency and the values predicted by the design calculations. The table shows that the measured collector efficiency was only one-half of the value used in the design calculations. Although no ASHRAE 93-77 test data were available from the manufacturer, a comparison with the test data for other collector models indicates that the design calculations for the collector performance were too optimistic. Also, a visual inspection revealed that the solar collectors have deteriorated rapidly. The materials used in the construction of the collector were apparently not rugged enough to withstand the severe environmental stresses experienced by solar collectors in this type of application. The manufacturer no longer makes this collector model.

Table 13 summarizes the performance of the solar system during the heating season. The average efficiency was only 9.2 percent. This value is abnormally low, amounting to slightly under half the value observed at Albuquerque and for other solar space heating systems. This is attributed to:

1. Low values for the instantaneous collector efficiency (Table 13)

2. A high tank temperature value, which forced the collectors to operate at high temperatures where thermal losses are larger.

The high tank temperature value indicates an improperly adjusted controls unit. This problem and the unsuccessful attempt to correct it are discussed under Field Experience later in this chapter.

The overall heat output of the collectors (107 MBtu) agrees with the amount of solar heat provided (84 MBtu) if a 20 percent loss factor for the solar storage tank is included. This magnitude of heat loss from the solar storage tank was inferred from examining the tank temperature decay rate during periods when no heat was being withdrawn. The loss rate of a well-designed storage tank would be in the range of 5 to 10 percent; the excessive loss of this tank can be attributed to the deterioration of the tank

Table 12

Monthly Summary of the Solar Collector Efficiency at the Battalion Headquarters Building at Fort Hood

Date	Hour	Fluid Parameter (°F-hr-ft²/Btu)	Measured Array Efficiency	Efficiency From Design Calculations
03/10/81	10:00	0.258	23%	58%
	11:00	0.237	25%	59%
	12:00	0.241	27%	59%
	13:00	0.217	27%	61%
	14:00	0.354	22%	50%
03/21/81	10:00	0.312	25%	54%
	11:00	0.240	22%	59%
	12:00	0.291	24%	55%
	13:00	0.208	30%	62%
	14:00	0.189	32%	63%
	15:00	0.219	28%	61%
04/30/81	11:00	0.259	25%	58%
	12:00	0.223	28%	61%
	13:00	0.231	27%	60%
	14:00	0.278	20%	56%
	15:00	0.338	14%	51%
05/01/81	12:00	0.260	24%	58%
	13:00	0.244	24%	59%
	14:00	0.248	23%	59%
05/18/81	12:00	0.197	48%	63%
	13:00	0.181	45%	64%
	14:00	0.174	37%	64%
	15:00	0.187	34%	63%

Table 13

Monthly Summary of Solar Collector Performance at Battalion Headquarters Building at Fort Hood

				SOLAR COLLECTORS		
Month	Average Outside Air Temperature (°F)	Incident Solar Energy (kBtu/ft²)	Average Solar Tank Temperature (°F)	Average Pump on-time (hrs/day)	Pump Electricity (kWH)	Energy Collected (MBtu)
01/81	55	24	143	3.8	382	17.9
02/81	55	24	123	3.4	398	18.1
03/81	64	45	126	5.1	888	45.5
04/81	76	45	139	3.5	588	10.7
05/81	78	53	148	4.3	745	12.6
06/81	84	16	179	5.1	316	1.7

insulation which occurred in September 1980, when holes were corroded in the tank and the ground around the tank was water soaked.

The pump operated an average 4.2 hours per day, which is a reasonable value. However, the ratio of the pumps' electrical energy consumption to the heat collected was 10.6 percent; this is about a factor of 2 higher than the normal value of 5 percent. This higher value is caused by the average collection efficiency value being lower (by a factor of 2) than expected.

Energy Savings

The energy savings during the heating season were calculated at 84 MBtu and the associated fuel cost savings amounted to roughly $500. Although more than 80 percent of the annual energy savings were to be provided during the cooling season, the solar system actually caused an increase in energy consumption during the cooling season because solar heating was supplied, thereby increasing the cooling load. Overall, the energy and fuel cost savings from the solar system are less than 20 percent of the expected value. Since the construction costs were greater than $500,000, the measured performance indicates that the system payback will be far greater than 25 years. Hence the system, as operating, is not proving to be economically feasible for this type of application.

The above assessment of the economic feasibility of this design is based on the measured energy performance of the system in which the absorption chiller was not operated. It is of interest to assess the economic feasibility assuming that the absorption chiller was operated successfully. Consequently, the space cooling loads were calculated for this building using the Building Loads and Systems Thermodynamics (BLAST) computer program (Table 14). Using a value of 3.3 for the Coefficient of Performance of a chiller and 6 cents/kWh for the cost of electricity, the total electricity consumption for a conventional cooling system would correspond to 49.3 MWh of electricity per year or an annual cost of $2960. Even if this potential savings were added to the space heating savings of $500 per year, the total potential savings would be only $3460 per year. Since the construction costs for the solar system amounted to over $500,000, the simple payback for this system would be far greater than 25 years and the system would not be economically feasible even if the absorption chiller were working perfectly.

Field Experience

Several problems occurred during the monitoring of this site. These problems provide valuable "lessons learned" for future designs. Operational problems with the HVAC system are discussed below, followed by a discussion of the monitoring equipment.

HVAC System Problems

The major HVAC system problems were:

- Large leaks in the solar storage tank caused by corrosion because of a failure to replace sacrificial anodes.

Table 14

Space Cooling Load Calculated for the Battalion Headquarters Building at Fort Hood*

Month	Space Cooling (10^6 Btu)	Peak Load (10^5 Btu/hr)
May	83	2.74
June	121	2.56
July	129	2.45
August	130	2.60
September	93	2.30
Total	556	

*Calculated with the BLAST computer program.

- High controls setpoint for the use of solar heating which could not be adjusted to the specified value.

- Spurious operation of the heating system simultaneous with cooling during summer.

- The solar cooling system did not function.

- Severe over-temperature conditions in the solar collectors caused by the absence of flow to the water side of the solar heat exchanger.

- Failure of the heat purge unit to operate when severe over-temperatures were reached.

The first major problem listed above, leaks in the solar storage tank, was noticed at the start of the heating season. At the start of the heating season, the solar storage tank was reported to have a large leak; i.e., it was losing water at the rate of about 10 gpm. The system was drained and the tank repaired by mid-November. However, the data indicate that this underground tank lost more thermal energy than normal. The leak may have saturated the tank insulation with water, thereby causing the tank to be lossy.

The other major HVAC problems are judged to result from control problems. During the heating season, the data indicated that the cut-off temperature for the use of solar energy was about 135°F, whereas the specifications called for a value of 100°F. The higher cut-off value forced the collectors to operate at a higher temperature, resulting in lower efficiency and lower heat output.

Although an attempt was made to adjust it to the specified value, the adjustment caused the conventional heating pump to operate continuously, so the control was returned to its original value.

Just before the cooling season began, the heating system operated intermittently even though the outside air temperatures indicated that there should be no building load. When the central cooling unit was started, the heating system began operating continuously, causing the cooling system to consume additional energy. After this was reported, the heating pump was manually shut off.

In addition to the faulty operation of the heating pump, there were other problems with controls during the cooling season. The absorption chiller did not start even though the tank temperature reached 180°F and higher. When the tank temperature reached 185°F, the flow of water to the water-side of the solar heat exchanger ceased. This caused extremely high temperatures (about 250°F) in the solar collector array. The heat purge unit failed to operate even though it was set to operate at temperatures above 220°F; this was judged to be due to the improper location of the control sensor for the heat purge unit.

During the next winter, the solar collectors were reported to have suffered freeze-damage because of a dilution of the ethylene glycol fluid in the collectors. The dilution of the fluid is attributed to the continuous occurrence of overtemperature conditions in the collectors (which causes loss of collector fluid) during the previous summer.

Overall, the experience at this site revealed severe problems with the controls. CERL studied the available information on the controls and conducted an on-site inspection. The inspection revealed that several control units were completely out of calibration.

Recommended Actions

The following actions are recommended to help alleviate problems in future systems.

<u>Design</u>.

1. Use simple, tested HVAC control strategies with the least susceptibility to failure.

2. Carefully consider the requirements for the proper location of control sensors and provide detailed design drawings illustrating the location and mounting details.

3. Specify control components which (a) do not require recalibration wherever possible and (b) contain built-in diagnostics to facilitate checking the units for proper operation.

4. Incorporate simple meters and switches to permit the system to be rapidly checked during operation and maintenance, particularly for protection features such as a heat purge unit.

5. Include provisions to alert maintenance personnel of the occurrence of overtemperature conditions (a simple light indicator can easily be added to the collector controls; a container placed beneath the pressure relief valve will collect fluid blown off and will also serve to alert personnel of a potential problem.)

Operation and Maintenance.

1. Replace sacrificial anodes per the schedule recommended by the manufacturer.

2. Check the operation of the HVAC system, particularly the controls, at the beginning of the heating season and at the beginning of the cooling season.

3. Periodically recalibrate control units that are known to need recalibration (for example, pneumatic receiver-controllers).

4. Check the level of freeze-protection of glycol-based collector fluids at the beginning of the heating season.

5. Check for indications of overtemperature conditions in the collector array. If overtemperatures are present, check for degradation in the collector fluid.

Monitoring Equipment

Several problems occurred with the monitoring equipment at this site. The experience provided the following recommended improvements for future monitoring of this type:

1. Rugged pressure transducers for flow measurements are needed to withstand the rigors of a field environment; the specifications for the units should provide pressure ratings which will withstand all possible conditions, including those that arise from operation by inexperienced personnel.

2. All wiring diagrams for the equipment should be applied by researchers at an early date. Wiring by contractors should be limited to extending wiring from sensors to an outlet panel; wiring from the panel to the equipment and checkout of the contractor's wiring should be performed by researchers.

3. Calibration checks of the temperature sensors should be planned in advance and executed at the same time as other checks of equipment.

4. Special efforts should be made to alert people to the monitoring effort and solicit cooperation and assistance in conducting the field research project.

6 RESULTS FOR THE EM BARRACKS BUILDING AT FORT HOOD

Data Analysis

The solar system at this site was monitored for about 6 months (December 1981 to July 1982). As noted earlier, the monitoring equipment at this site consisted of BTU-Meters. The BTU-Meter readings did not advance during the monitoring interval. Hence, the data indicate that no solar energy was collected and no solar heating was provided for the building's DHW system. A visual inspection by CERL and the site POC revealed that the solar collection pumps had been manually turned off. No reason was found for shutting down the solar components.

Since the solar components were not operating, the solar energy savings and the solar collector efficiency were zero.

Lessons Learned

Generally, simple DHW systems offer the best payback and have the smallest O&M requirements of any solar system. The only problem reported for this system involved the solar controls. It was reported that the controls were causing the collection pumps to operate continuously; the solar heat collected during the day was then lost at night.

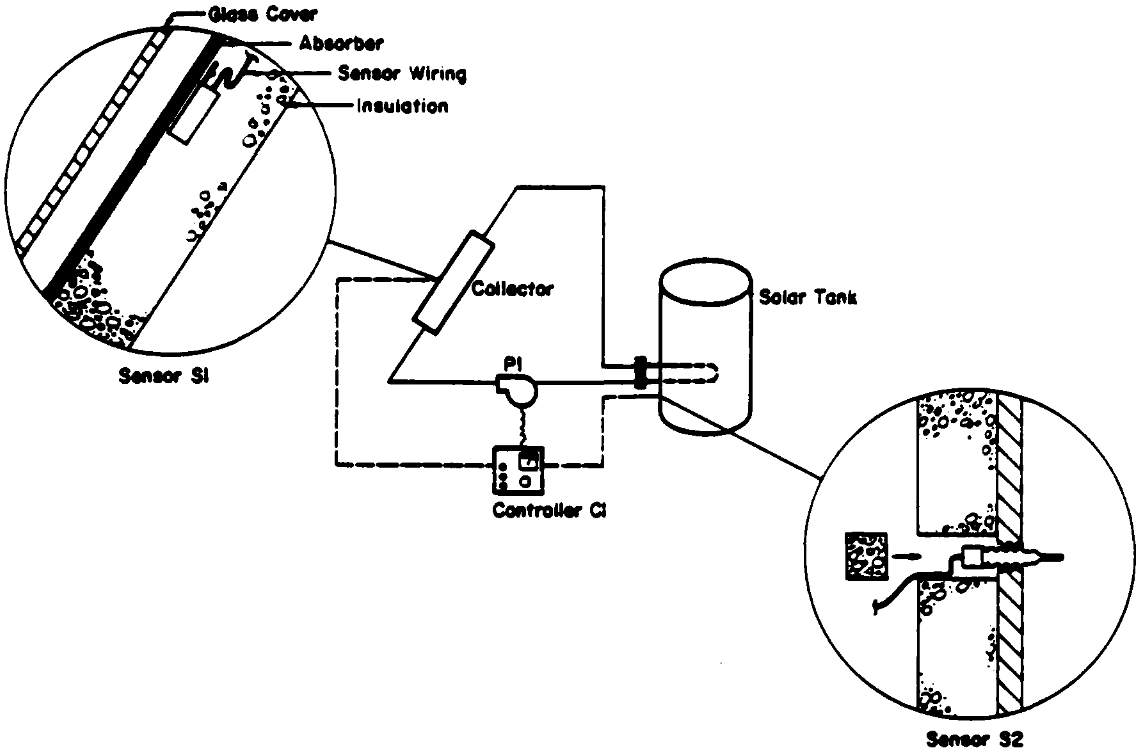
The solar controls strategy specified for this system is rather unusual since it involves the sequential use of the dual solar storage tanks. Since other DHW systems have been reported to operate successfully when provided with proper controls, the solar components at this site should function properly and provide excellent performance if provided with proper controls.

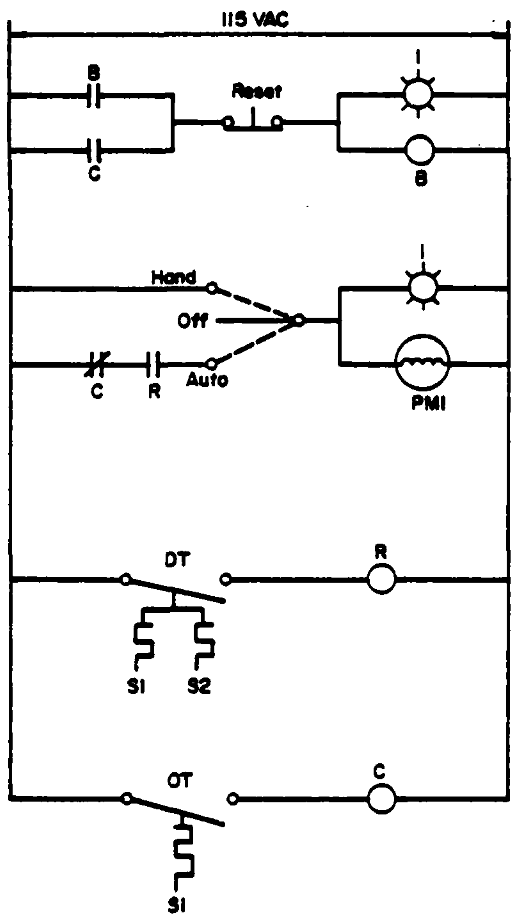
Controls for DHW System

Since the controls were a major problem at this site, recommendations for controls of DHW systems were developed. Figure 12 illustrates a controls strategy recommended for a small DHW system (two or three collectors) with in-tank heat exchangers. The figure includes a simple sketch of the collector loop of a system with an in-tank exchanger with the sensor locations highlighted. It also shows a ladder schematic and sequence of operations to fully explain the control strategy.

A commercial controls unit with built-in diagnostics, labeled C1 in the figure, is combined with other simple parts (relay, switches, and indicator lamp) to provide a reliable, efficient control system that can be quickly checked during operation and maintenance.

Since the DHW system at this site is larger and involves two solar storage tanks, a separate controls strategy was devised using the previous one as a basis. Figure 13 is a simple sketch of the DHW system with two tanks and an external heat exchanger. The design takes advantage of potential benefits from thermal stratification by the appropriate piping arrangement of the two





SEQUENCE OF OPERATIONS

In normal operation, thermostat OT is open Collector pump P1 is energized when collector temperature exceeds tank temperature by 15°F (S1 - S2 > 15°F). Pump P1 is de-energized when the difference S1-S2 decreases to 5°F or less.

When the collector temperature exceeds the maximum safe operating temperature for the collector pump (210°F), thermostat OT closes and causes: (1) prevents Pump P1 from being energized, (2) energizes overtemperature indicator lamp. Once energized, the lamp remains on until manually reset by operator.

LEGEND

I	Indicator lamp
B	Relay
C	" "
R	" "
PM1	pump motor, pump P1
DT	Differential thermostat
OT	Overtemperature thermostat
S_x	sensors for controller

Note: Thermostats DT & OT and relays C & R are in controller C1.

Figure 12. Controls strategy for small DHW system.

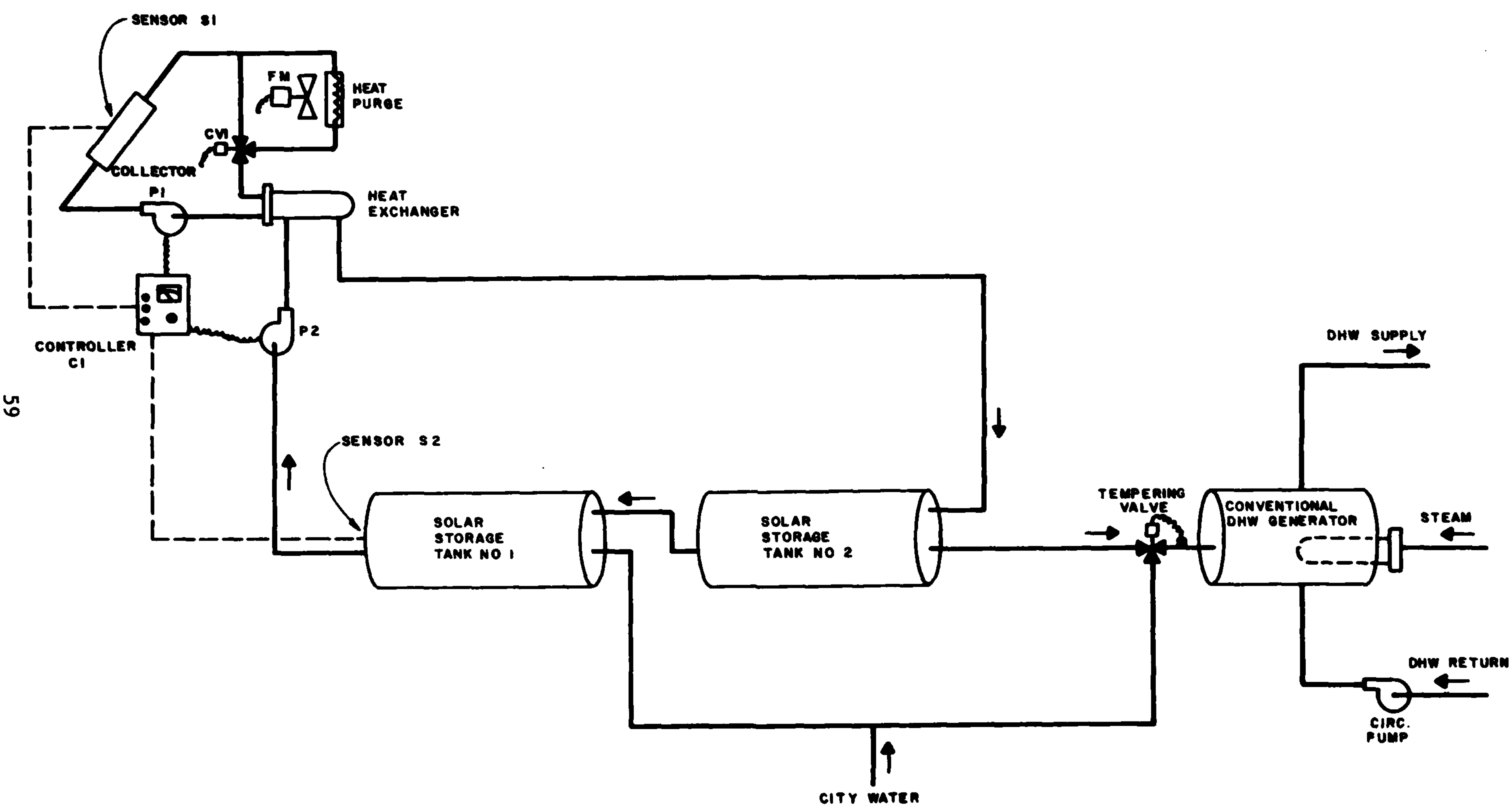


Figure 13. Schematic of DHW system with dual tanks and roof-mounted heat purge unit.

tanks. With this arrangement, the same simple strategy for controlling the collection pumps can be used.

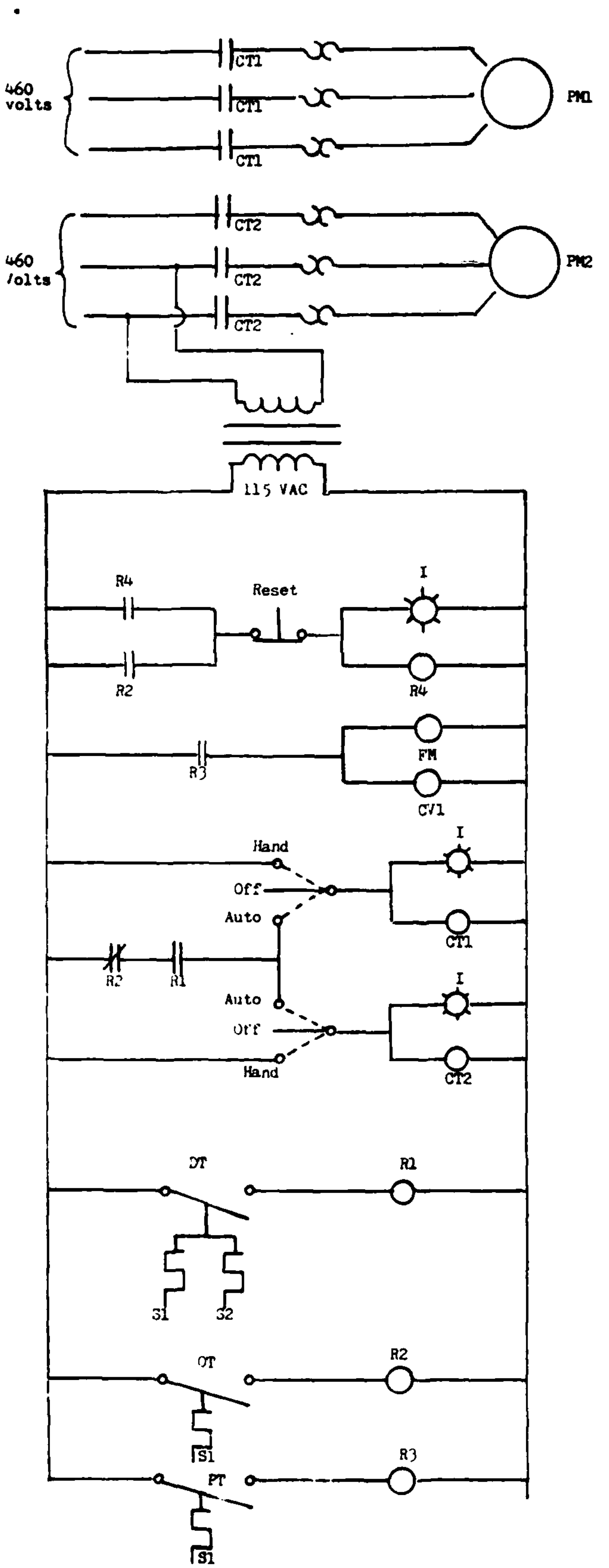
Figure 14 provides a ladder schematic and sequence of operations for this arrangement. In this design, a simple controller with built-up diagnostics (labeled CT1 in the figure) can be combined with a few simple parts (relays, switches, and indicator lamps) to provide a high-quality control unit with provisions for rapid checking by maintenance personnel. Since the existing design at this site includes a roof-mounted heat purge unit, the control of this unit is also included in a straightforward manner in the figure.

Since DHW systems rarely have excess heat to purge, a technique for including a heat purge capability at lower cost was developed for future designs of DHW systems of this size and type. Figure 15 illustrates the recommended strategy. A small solenoid valve is operated by controller C1 and automatically dumps water from the solar tank to a floor drain. The method accomplishes the heat purge with an inexpensive (less than $100), reliable component and without additional control units. Since the amount of heat to be expelled is small and the technique involves dumping relatively hot (180 to 190°F) water, it is judged that only a small amount of water is used by this technique.

Experience With BTU-Meters

BTU-Meters are relatively new devices that show promise for future monitoring work. It was expected that the monitoring at this site would provide useful experience with the field application of the meter. However, the lack of operation of the solar system prevented this.

Since the meters are potentially useful in measuring energy performance for a wide range of applications, this type of meter will be considered for use in future monitoring studies. One goal of the initial field application of the meter will be evaluation of its performance in a field application.



SEQUENCE OF OPERATIONS

In normal operation, thermostat OT is open and thermostat PT is open (heat purge unit off). Collector pump P1 and tank pump P2 are energized when the collector temperature exceeds the tank temperature by 15°F (S1 - S2 15°F). Pumps P1 and P2 are de-energized when the difference S1 - S2 decreases to 5°F or less.

If the collector temperature exceeds the upper limit (210°F), thermostat PT energizes solenoid valve CV1 and fan motor FM for heat purge unit. Flow through the collectors is then diverted through the heat purge unit, expelling excess heat to the outside air. The heat purge unit is deactivated when the collector temperature drops to 203°F or lower.

If the collector temperature exceeds the maximum safe temperature for operating the collector pump (230°F), thermostat OT closes and causes: (1) R2 is energized to prevent collector pump from being energized and (2) overtemperature indicator lamp to be energized. When the collector temperature drops to 223°F or lower, thermostat OT opens allowing collector pump to operate normally. However, overtemperature indicator lamp remains on until manually reset by operator.

LEGEND

I Indicator lamp

R_x Relay

PM Pump Motor

DT Differential thermostat

OT Overtemperature thermostat

PT Heat Purge thermostat

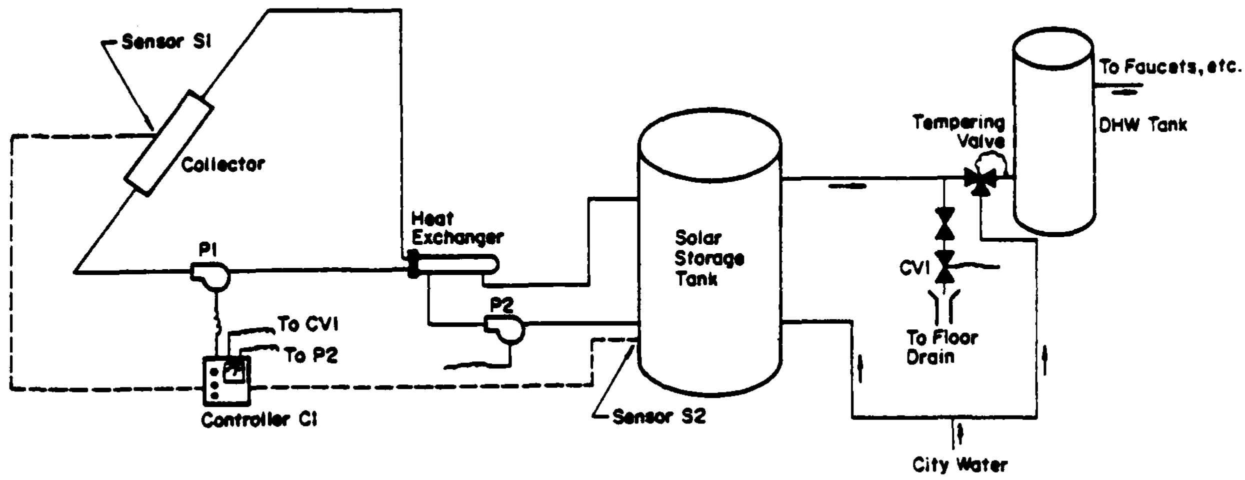
S_x Sensors for controller

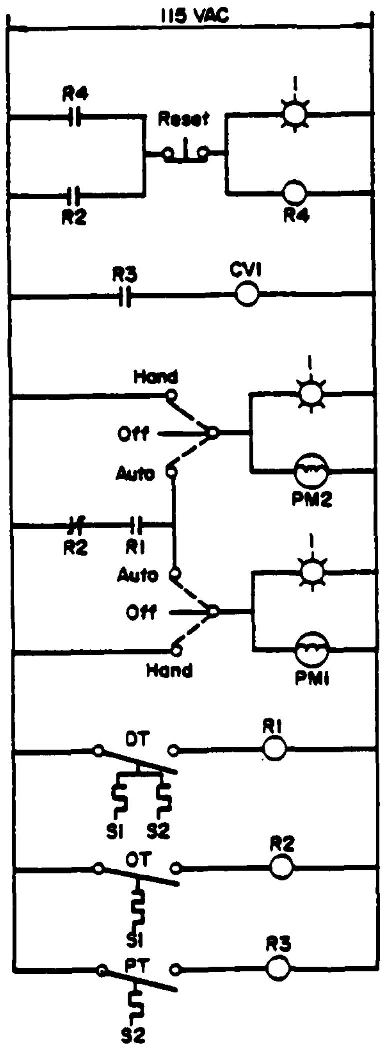
CV1 Solenoid valve in heat purge unit

FM Fan motor in heat purge unit

CT_x Contactors for pump motors

Figure 14. Controls diagram for DHW system illustrated in Figure 13.





SEQUENCE OF OPERATIONS

In normal operation, thermostat OT is open and thermostat PT is open (valve CV1 is closed). Collector pump P1 is energized when collector temperature exceeds tank temperature by 15°F (S1 - S2 > 15°F). Pump P1 is de-energized when the difference S1-S2 decreases to 5°F or less.

If the solar tank temperature exceeds the upper limit (200°F), thermostat PT energizes solenoid valve CV1. CV1 then opens and dumps hot water down the drain until the tank temperature drops to 193°F.

If the collector temperature exceeds the maximum safe temperatu[illegible] for operating the collector pump (230°F), thermostat OT closed causing: (1) R2 to prevent collector pump from being energized and (2) energize the overtemperature indicator lamp. Once it is energized, the lamp remains on until manually reset.

LEGEND

I	Indicator lamp
R_x	Relay
PM	pump motor
DT	Differential thermostat
OT	Overtemperature thermostat
PT	Heat purge thermostat
S_x	Sensors for controller
CV1	Solenoid valve for heat purge

Note: Thermostats DT, OT, and PT and relays R1, R2, & R3 are in controller C1.

Figure 15. Recommended controls strategy for large DHW systems.

7 RESULTS FOR THE SEAGOVILLE RESERVE CENTER

Data were collected from the Seagoville site from December 1980 through March 1982. Data for two heating seasons and one cooling season (roughly corresponding to 16 months) were obtained.

Although the solar design at this site is virtually identical to the one at Albuquerque, it was not possible to do a detailed analysis and comparison with the design calculations because of the unusual operating conditions which persisted throughout the monitoring interval at this site. Consequently, this chapter describes the behavior observed in the data and estimates the system performance that would have to be provided under normal operating conditions. Also, field operating conditions are summarized and correlated to the observed behavior.

Data Evaluation -- First Heating Season

When the monitoring was first initiated (December 1980), the following system behavior was observed from the data:

- The collector pump operated 24 hours a day, thereby causing a large loss of solar heat.

- The solar storage tank temperature would typically be 70°F at night and increase to about 110°F on a sunny day.

- There was no heating for the building from any source.

On 6 January 1981, the collector pump began operating normally, but no space heating was being provided. By 14 January (the date of the meeting with the maintenance contractor described below), the solar storage tank temperature had increased to 175°F. However, the data indicate that little or no heat was being delivered to the building from any source. The data show that the controls attempted to operate the absorption chiller to provide solar cooling on 14 January. This happened again on 20 January and occurred continuously until 30 January. The data indicate that little or no heating was provided to the building from any source throughout the interval from December to February 1981.

In February 1981, space heating from solar was provided for the first time. During the interval from 3 February to 20 March, solar space heating was available continuously to supply 100 percent of the building load. The system controls attempted to operate the absorption chiller intermittently throughout this interval, thereby wasting heat.

Data Evaluation -- Cooling Season

The data indicate that a severe problem with the solar system occurred just at the end of the first heating season. On 20 March, the flow to the water side of the heat exchanger was blocked because a manual isolation valve closed. Since the heat removal was stopped, the collectors reached high temperatures (up to 270°F). The combination of high temperatures and pressures damaged the collector piping. The collectors were drained so repairs could be made.

During the summer, the system behavior was observed to be as follows:

- The reciprocating chiller operated to provide space cooling.

- The solar collectors did not operate (collector fluid was drained).

- No solar cooling was provided since the absorption chiller did not operate.

In the fall, the solar system was again filled with collector fluid and operated to provide DHW heating since the DHW boiler was still not functioning and there was no other source for DHW heating (the DHW boiler had become inoperable before December 1980).

Date Evaluation -- Second Heating Season

At the beginning of the second heating season, the solar system appeared to be operating satisfactorily. The tank temperature typically varied between 180 to 195°F during the interval of 20 September 1981 to 22 September 1981. However, on 23 September, the system began supplying space heat from the solar storage tank and the tank temperature rapidly decreased. By the middle of November, the tank temperature was operating in the interval of 130 to 145°F. The control of the space heating system appeared to be irregular during this first part of the heating season; the system would operate continuously for several days at a time and then stop.

From 1 December 1981 until 10 March 1982, the heating system operated continuously, supplying heat to the building from the solar storage tank. (The reciprocating chiller was turned on 10 March 1982 to provide space cooling for the building.) During the interval of 1 December 1981 to 10 March 1982, the system appeared to be operating out of control. As detailed below in the discussion of HVAC system problems, the pneumatic control system had been severely damaged during the previous summer and was not functioning.

With the heating system running continuously and out of control throughout the interval, the system functioned as follows:

- The fan-coil units were supplied with water from the solar storage tank regardless of the tank temperature.

- On warm sunny days, the solar collectors would deliver large quantities of heat to the solar storage tank and the building would simultaneously receive a large amount of heat input.

- On subsequent cold and cloudy days, the solar tank temperature would drop to as low as 70°F and no space heating would be provided to the building.

- Part of the solar heat was lost because the mechanical room piping leaked (the water loss was automatically made up by the system from the relatively cold city water supply); this contributed to the rapid decrease in tank temperature at the end of a warm, sunny day.

The building load and the heat output of the solar collectors during the second heating season for this site do not correspond to a system operating under reasonable conditions. The backup did not operate during the first half of the heating season and consequently there were intervals when the building's heating need was not met. Although the backup boiler began functioning intermittently on 14 January 1982, its heating was supplied simultaneously with direct solar heating.

Solar Collector Performance

Table 15 lists the values of the instantaneous collector efficiency and compares them to the test values from the manufacturer for a single collector. The data show that the collectors at Seagoville were operating at about two-thirds of the expected values. Because of the similarity between the Seagoville solar collectors and the Albuquerque solar collectors (the same model number and from the same manufacturer, the same overall design), it is believed that the anomalously low efficiency values were caused by the operating conditions. Specifically, onsite personnel indicated that the collectors were not filled properly. Hence, the inefficiency may have been caused by air blockages.

Since the collectors operated under abnormal conditions (very low tank temperature values), no useful comparison can be made between the measured performance (average efficiency and heat output) and the design values.

Energy Savings Estimate

Although the system did not provide 100 percent of the space heating for this building, the data indicate that the solar portion of the system had more than enough capacity to provide 100 percent of the space heating and DHW heating for this building. The system's inferior performance during the two heating seasons is attributed to the abnormal operating conditions. The energy savings would be expected to be about 150 MBtu per year (a cost savings of $900).

No solar cooling was provided at the site and hence no energy savings for space cooling were produced by the solar components. By examining the calculated cooling load, it was determined that the solar components might have saved $6000 in electricity costs for the chiller if solar cooling had been provided. After adding this to the savings in fuel for the boiler, the total potential savings in energy costs by the solar components is below $10,000 per year.

The potential savings by the solar components can be evaluated by comparison to the construction costs and the O&M costs. The complex solar system at this site added more than $500,000 to the construction costs for the building and had the same high O&M costs ($30,000 per year) as the Albuquerque

Table 15

Comparison of the Measured Collector Efficiency at Seagoville With the Manufacturer's Test Data for a Single Collector

Date	Hour	Fluid Parameter (°F-hr-ft²/Btu)	Measured Array Efficiency	Efficiency From Test Data
12/05/81	10:00	0.318	25%	45%
	11:00	0.282	30%	48%
	12:00	0.334	31%	43%
	13:00	0.344	26%	42%
12/25/81	11:00	0.210	33%	55%
	12:00	0.213	35%	55%
	13:00	0.243	34%	52%
	14:00	0.318	30%	45%
01/06/82	11:00	0.239	34%	52%
	12:00	0.208	36%	55%
	13:00	0.200	38%	56%
	14:00	0.252	38%	51%
02/14/82	12:00	0.182	28%	58%
	13:00	0.194	30%	57%
	14:00	0.238	30%	53%
03/07/82	11:00	0.182	37%	58%
	12:00	0.195	42%	56%
	13:00	0.218	41%	54%
	14:00	0.255	40%	51%
	15:00	0.298	35%	47%
03/22/82	11:00	0.140	40%	61%
	12:00	0.152	43%	60%
	13:00	0.171	45%	59%
	14:00	0.213	43%	55%
	15:00	0.330	34%	44%

building. Even if the O&M costs are neglected, the comparison of costs to savings shows that the system has a payback time greater than 25 years; this indicates that solar applications of this type are not economically feasible.

HVAC System Problems -- First Heating Season

The monitoring data revealed that the HVAC system at this site operated under unusual conditions which arose from various problems with the HVAC components at the site. The problems were tabulated as part of the "lessons learned" from the field experience.

Problems that occurred from December 1980 to 14 January 1981 were summarized during a meeting on 14 January 1981 attended by CERL, the building user, the Fort Worth District, and the maintenance contractor. The building user presented a long list of improper O&M actions by the maintenance contractor during the first part of the heating season. Included in the list were:

- The collector pump was turned on manually and left to run 24 hours a day, which resulted in large energy losses from the solar storage tank.

- The bleed valves on the collector array were left open for a long time interval and ethylene glycol solution was discharged onto the roof.

- The bleed valve on the fuel oil line to the DHW boiler was left open and fuel oil was dumped into a city sewer.

- Excessively high pressures were being generated in the HVAC piping.

The user also described the effects of the operating conditions as follows:

- The metered fuel oil consumption rate of the DHW boiler for the first 3 months of this heating season was six times higher than the previous rate of consumption.

- The building had been without space heating for more than a month and without DHW heating for more than 2 months.

- Both backup sources of heating (the DHW boiler and waste heat recovery by reciprocating chiller) were not functioning.

When CERL visited the site to attend the joint meeting, the monitoring equipment indicated that the absorption chiller was being placed in operation by the automatic controls unit, despite the dire need for space heat and the time of year (14 January). The operation of the absorption chiller was confirmed by a visual inspection of the HVAC equipment. The problem was traced to an inappropriate use of the "AUTO" position for the seasonal selection switch. This switch allows the user to select the seasonal mode, either "wintertime" or "summertime." The Fort Worth District had previously pointed out that the "AUTO" position on this switch was not to be used.

HVAC System Problems -- Cooling Season

Despite the meeting with the maintenance contractor, problems with the HVAC system operation continued and the condition of the equipment deteriorated throughout the summer.

The monitoring data indicated that at 13:10 on 20 March 1981, a blockage of flow occurred on the water side of the solar heat exchanger. The blockage stopped the delivery of heat from the collectors to the storage tank and caused the generation of extremely high temperatures (as high as 270°F) in the solar collectors. CERL notified Corps field personnel and the subsequent on-site inspection revealed that an isolation valve had been manually closed. It was noted that maintenance personnel had been there to repair a small leak in an automatic valve on the date with the blockage occurred.

The combination of high temperature and pressure associated with the steam generation placed large stresses on the collector piping and leaks in the piping were reported by the user. The collector system was then drained and the piping repaired. Although operation of the solar system resumed later in the summer, its expressed purpose was to provide DHW heating (the DHW boiler was still not functional). The absorption chiller was not operated to provide space cooling throughout the summer; severe problems were being experienced with other HVAC components and the reciprocating chiller was available to provide space cooling.

HVAC System Problems -- Second Heating Season

The condition of the HVAC equipment had deteriorated markedly during the previous year. At the beginning of the second heating season, virtually all components in the mechanical room were reported to be inoperable. Only the solar system remained in operable condition, but its heat output was being lost through large leaks.

The status of the building at the beginning of the second heating season was:

- The compressor motor on the reciprocating chiller was burned out.

- The compressor motor for the air compressor, which operated the pneumatic controls system, was burned out.

- The pneumatic control lines, including those that led to thermostats in the building, were filled with water and oil.

- The DHW boiler was still inoperable.

- There were several leaks in the piping and components in the mechanical room. Solar-heated water was flowing out of the mechanical room across the parking lot.

The effect of these conditions on the monitoring data was evident since the building was functioning with no operable controls. For example, a large amount of solar heat was collected and delivered to the building on warm, sunny days (highs in the 60s). On subsequent cloudy and cold days, the solar storage tank temperature dropped to 70°F and no heat was delivered to the building.

Monitoring Equipment

Some of the monitoring equipment malfunctioned at the Seagoville site, which affected the data collection. These malfunctions were tabulated as "lessons learned" for future monitoring studies.

Difficulties experienced during the installation of some monitoring components by the construction contractor were pointed out by CERL. However, other facets of the construction work took precedence over monitoring, and arrangements made for correcting the deficiencies as part of the follow-on contract fell through when the contract was not approved.

The following two electric power sensors were found to be malfunctioning during the trip to initiate the data flow:

1. The sensor for measuring total building electrical consumption.

2. The sensor for measuring the electrical consumption by the reciprocating chiller, which provided backup for space cooling.

After the data collection started, arrangements were made to repair these sensors. However, the arrangements were cancelled by the Fort Worth District when other, severe problems with the HVAC system assumed a higher O&M priority.

Repeated difficulties were also experienced with the insertable turbine probes used for flow measurements. Shortly after the data flow was initiated, all flow signals were absent. An inspection revealed that the sensors had been pushed out of the pipes, presumably because of the excessively high pressure in the piping (see the previous discussion of the problems encountered during the first heating season). Also, two turbine units were so severely damaged they required replacement. Although the manufacturer specified a maximum working pressure of 150 psi, a second loss of flow signals occurred shortly after the sensors were re-inserted into the piping. Consequently, CERL designed a locking mechanism to hold the flow sensors in the piping and also repaired the damaged turbine elements. This work was completed at the end of the first heating season and flow values were then obtained for the cooling season and the second heating season without further difficulty.

The overall experience with the turbine probe sensors indicates that the units are not rugged enough for field use. It is recommended that future investigations use the venturi sensor which proved to be so successful during the monitoring at the Albuquerque building.

8 CONCLUSIONS AND RECOMMENDATIONS

Four solar HVAC systems were monitored for a period of about 1 year. The conclusions drawn from this monitoring study are listed below.

1. Energy Savings by Solar. All four of the solar systems failed to provide the energy savings predicted by the design calculations done by the A/E firms.

2. Fuel Cost Savings and Economic Feasibility. Based on the fuel cost savings measured during the monitoring period, all four solar systems have simple payback periods greater than 25 years. Calculations indicate that even if the solar cooling units had worked, the simple payback periods for the three solar heating and cooling systems would still be greater than 25 years.

3. Dependence on O&M Performance. The O&M of the solar systems was a key factor in their overall performance.

4. Controls Failures. Controls failures occurred in each of the four systems. These failures had a pronounced effect on the system performance for all but one of the systems. The only exception occurred because a building occupant intervened (effectively functioning as a dedicated building operator) and manually operated the system.

The three largest solar systems in this study included the function of solar-assisted space cooling. For these systems, the following additional conclusions were generated:

1. Space Cooling from Solar. Each of the systems failed to provide any space cooling from using solar energy. In a similar ASHRAE study of nine solar cooling systems, most of the nine solar cooling systems were found to be net energy losers.[7] In a performance evaluation of solar cooling systems monitored by the National Solar Data Network, solar cooling systems were found to be not cost-effective in terms of reasonable payback periods.[8] Hence, the feasibility of solar cooling systems is questionable with the current level of solar cooling technology.

2. Damage to Major HVAC Components. At least one major HVAC component (absorption chiller, solar collector array, reciprocating chiller, etc.) in each of the three systems was severely damaged in the first 2 or 3 years of operation.

3. Overtemperature Conditions in Solar Collectors. Two of the three systems experienced overtemperature conditions in the solar collector arrays. The only exception occurred because a building occupant manually operated the system. Although the manual operation of this one system prevented damage to the solar collectors at that site, this heat rejection method wasted energy and significantly increased energy costs. In general, solar systems sized for

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[7] D. Ward and H. Oberoi, Handbook of Experiences in the Design and Installation of Solar Heating and Cooling Systems (ASHRAE, 1980).

[8] P. Wetzel and P. Pakkala, Comparative Report: Performance of Active Solar Space Cooling Systems, Solar/0023-82/40 (U.S. Department of Energy, 1982).

space heating and cooling must have heat purge units to efficiently and automatically reject excess heat. This will prevent overtemperature conditions in the collectors.

4. Complexity/O&M. The complexity of the HVAC systems and controls posed a major O&M problem for each system. In particular, it was very difficult to determine a system's status, and the complexity of the systems made them failure-prone. Morever, the systems were not designed to fail in a safe, efficient mode of operation. They did not have simple manual override features to permit manual operation while malfunctions were being repaired.

There were too many modes of operation for the reserve centers. Even if the systems executed the modes correctly, the additional costs of providing the modes is not justified by the small energy savings they would theoretically provide. The performance limitations of HVAC components is such that added modes actually increase energy consumption in most instances. The EMCS systems at the reserve centers were more failure-prone than the HVAC components. This contributed to rather than prevented O&M problems. The added costs of the EMCS systems were not justified by the energy savings they might have provided if they had functioned.

5. Failure-Prone Design. The overall failure pattern observed in this study was:

a. The systems had many controllers and controlled units which had a given failure rate. Because there were many such units, the systems were failure-prone.

b. The systems' O&M requirements exceeded the level currently allowed for Army buildings. Consequently, the O&M needs of the HVAC systems were not met.

c. Inadequate O&M led to system malfunctions and severe damage to some HVAC components. O&M problems also caused the solar portions of the systems to perform relatively poorly.

6. Problems With Solar Components. The four solar systems in this study were designed and constructed as part of the first application of solar systems to Army buildings. Some of the problems with the solar systems are a result of the introduction of new technology at an early stage in its development. In the time since the systems were designed and constructed, more refine design guidelines have been produced and their use will eliminate some of the solar problems.

7. Use of Untested HVAC Concepts. Although there were some problems with solar components, many of the system failures and problems reflect the attempt to use (a) untested techniques to control HVAC and DHW systems and (b) untested HVAC system configurations. When the systems were designed, few, if any, tested solar configurations and control strategies were available to designers. The approach widely used by designers was to (a) devise configurations and control strategies as part of the design work and (b) treat many design tasks, such as writing specifications for components and providing details for locating sensors, in much the same way followed for conventional systems.

This study has revealed the high costs, poor performance, and excessive O&M requirements associated with attempts to use untested energy system concepts in the field. A thorough experimental test at a research laboratory would have revealed many of the shortcomings in the designs. The experience demonstrates the need for a team effort by Corps Districts and researchers when introducing new technology in field applications, including a thorough evaluation of concepts, strategies, and hardware performance at a research laboratory followed by a field demonstration which is carefully monitored and evaluated.

The following are recommended to improve the future design of solar-assisted HVAC systems:

1. Determination of Solar Feasibility. Any calculation that indicates that the incorporation of a solar energy system in a prospective building is economically justified should be carefully studied. The SOLFEAS computer program developed jointly by the Fort Worth District and CERL should be used to calculate the economic feasibility of including solar systems in Army building designs.[9]

2. Solar Space Cooling. Based on current economic guidance and existing solar technology, solar-assisted cooling is not economically feasible. Solar space cooling, especially with flat-plate solar collectors, should not be included in future designs until a breakthrough in solar cooling technology occurs and it has been proven that the new technology allows efficient, reliable solar cooling systems to be installed in Army buildings.

3. Simplicity of Design. Simplicity should be stressed in future designs. The addition of extra components or extra modes of operation should be carefully examined to determine if the expected energy savings justify the added complexity and costs. If more than one mode of operation is to be included in a design, the sequence of operations should be stated clearly and each mode of operation should be illustrated on a separate schematic diagram of the system.

4. Heat Pump/Waste Heat Recovery. A reciprocating chiller should not be used as a heat pump to recover waste heat in future designs, particularly in reserve centers or buildings with a similar occupancy schedule. Only units that are designed by manufacturers to operate as heat pumps should be considered for applications as heat pumps. The design of a system with both a heat pump and a solar energy system is questionable practice. A proposal for such a combination should be examined thoroughly before incorporating it into an HVAC system design.

5. Designs Based on Proven Technologies. Only proven technologies should be implemented in future designs. New designs should be thoroughly tested in the laboratory and demonstrated as complete systems in the field before being considered as acceptable design practice. When new designs are

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[9] D. M. Joncich and C. W. Sohn, SOLFEAS: An Interactive Program for Estimating the Economic Feasibility of an Active Solar Thermal Energy System, Technical Report E-180/ADA125682 (CERL, 1983).

needed, they should be developed as part of a team effort with active participation by Corps Districts, Facilities Engineers, and researchers.

6. O&M Requirements. More emphasis should be placed on the O&M requirements of the system during design. Designers should be required to clearly define a design's periodic maintenance requirements. That information should be given to the Facilities Engineer or included in the maintenance contract.

7. Acceptance Testing With Simple Meters. An acceptance test, in which measured performance is compared to specified performance, should be required before final acceptance of a solar energy system.[10] Requirements for an acceptance test and the meters for performance measurements should be included in the construction specifications. The meters, permanently installed by the contractor at the same time as the other solar components, can then be used to help the system's O&M. These meters let maintenance personnel detect failures and pinpoint the cause of the failure.

HVAC System Control. When devising a controls strategy for an HVAC system, designers must be aware of the limited abilities of the control components ordinarily specified and installed for HVAC systems, particularly the pneumatic controls. If ordinary HVAC controls components are to be stipulated in the design specifications, the designer should use simple on/off controls and a simple control strategy wherever possible.

Complex control strategies should not be incorporated in future designs until the requirements for control components have been determined and the ability of the components to execute such strategies has been tested in a laboratory and proven in a field demonstration.

Table 16 lists specific recommendations for improving the technical aspects of solar designs. The table indicates the specific problem noted in the monitoring study and the recommended approach to solving it.

[10] D. L. Johnson and D. M. Joncich, Procedures for Acceptance Testing of Solar Energy Systems, Technical Report E-192/ADA141839 (CERL, 1984).

Table 16

Recommendations for Improving the Technical Aspects of Future Solar Designs

Deficiency Found in Monitoring Study	Recommended Approach to Solution
Specification of collector efficiency	Use expected operating interval as basis for the specification of collector efficiency. If detailed computer simulation results are not available, use guidelines* to obtain the operating interval.
Mounting of control sensors for activating solar collection pump(s).	Proper mounting of the control sensors should be described in detail and illustrated on drawings. Proper mounting is as follows: 1. Collector sensor should be firmly bonded to the absorber plate, preferably to the underside. 2. Tank sensor should be immersed in tank fluid near the tank outlet (mounting on a pipe from the tank is not acceptable).
Low-temperature limit for operation of absorption chiller	Controls should be provided to permit operation of the absorption chiller only when the generator inlet temperature is 170°F or higher.
Air bleed valves for collector array	If manual bleed valves are provided, access to the valves should be provided to facilitate maintenance. Otherwise, automatic air bleed valves should be specified.
Location of control sensor for heat purge unit	Control sensor should be mounted in collector return pipe to protect collector array from overtemperature conditions (not in solar storage tank). The controls unit for the heat purge device should contain built-in diagnostics and provide manual override capability. (Commercial controls units are available with these features and allow a single unit to control the activation of collection pump and heat purge unit.)

*Department of Energy guidelines are given in <u>Introduction to Solar Heating and Cooling Design and Sizing</u>, DOE/CS-0011 (Department of Energy, 1978).

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APPENDIX:

DESCRIPTION OF BTU-METERS

Thermal energy must be transferred by HVAC components to perform DHW heating, space heating, and space cooling. Consequently, the measurement of heat input/output from HVAC components is of fundamental importance for the evaluation of HVAC system performance. In particular, the performance evaluation of a solar collector array requires a measurement of the array's heat output.

This appendix describes a simple meter which measures heat transfer: the BTU-Meter. The operation of this meter for thermal energy measurements is analogous to the kilowatt-hour meter for electrical energy measurements. Figure A1 shows the similarities between the BTU-Meter and the kilowatt-hour meter widely used by utility companies for electricity measurements. Both meters involve measurements on the supply and return lines to a device and both sum the energy transfer to or from that device.

The following paragraphs describe how a BTU-Meter works and give general considerations for applying BTU-Meters to HVAC system performance measurements.

How the BTU Meter Works

For an hydronic system, the thermal energy transfer to or from an HVAC component is given by the following equation:

$$Q = \int C_p \dot{M} (T_o - T_i)dt \qquad \text{[Eq A3]}$$

where:

Q = heat output or input by the heat transfer fluid

C_p = specific heat capacity of the heat transfer fluid

$\dot{M}$ = mass flow rate of the fluid

T_i, T_o = the inlet and outlet temperatures of the fluid, respectively

t = time.

Figure A2 shows the basic elements of a BTU-Meter which can measure the heat transfer given by Eq A1. These elements include: (1) sensors to detect the flow and temperatures used in Eq A1; (2) an electronic computer to calculate the rate of heat transfer; and (3) a component to display the results to the operator.

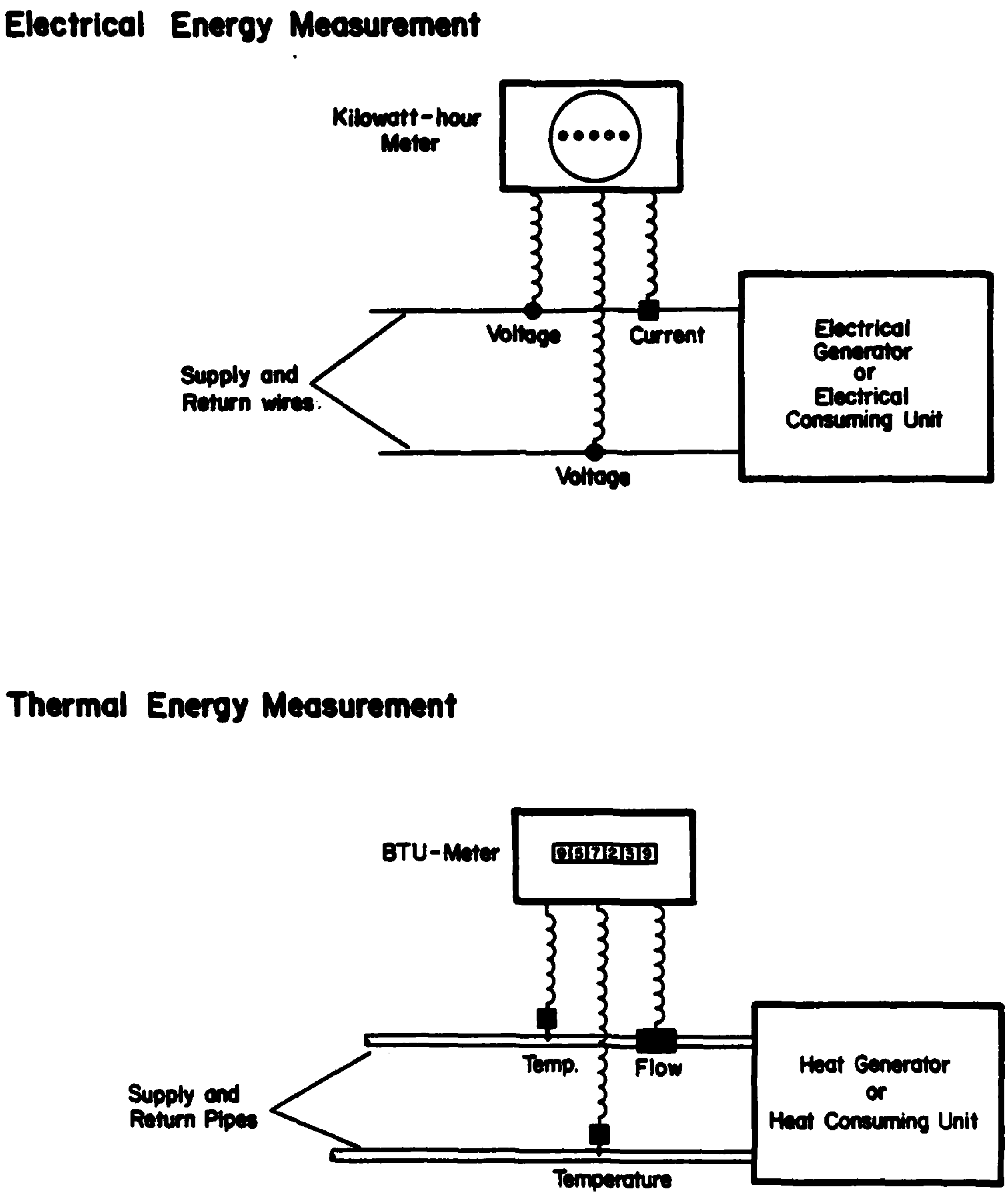

Figure A1. Similarities between BTU-Meter and kilowatt-hour meter.

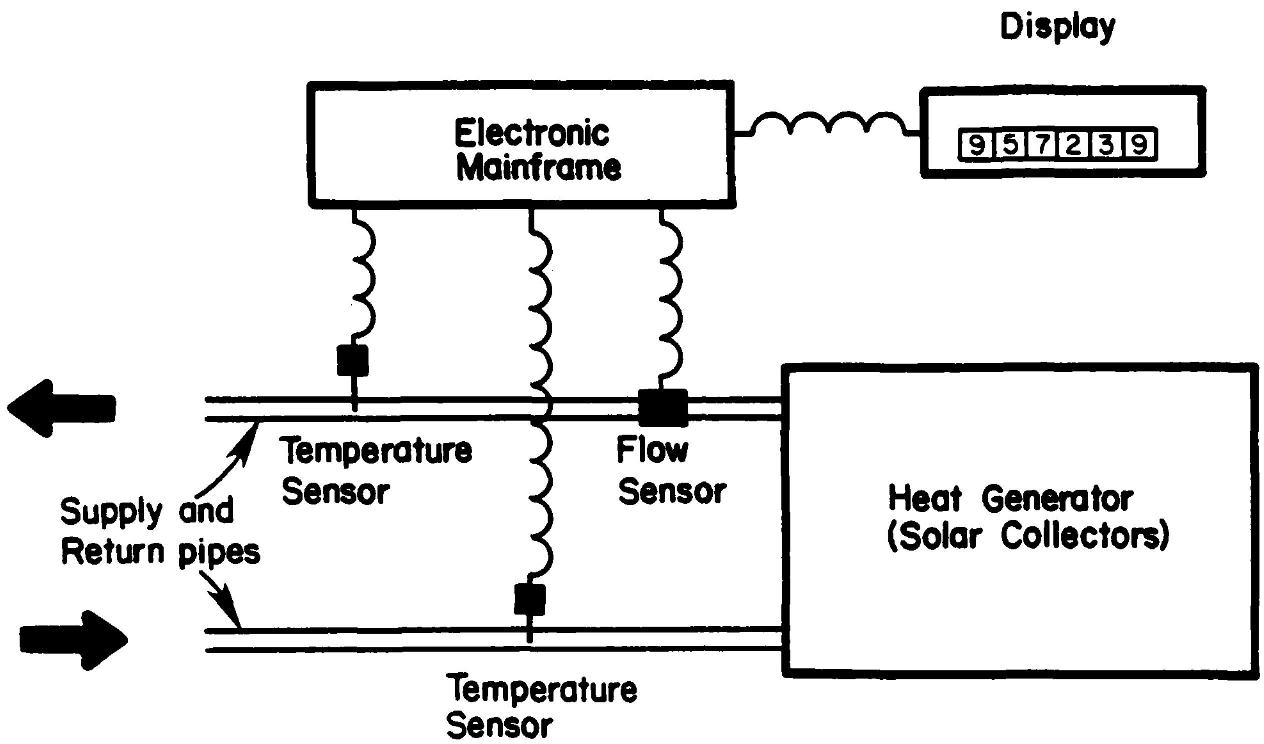

Figure A2. Basic elements of BTU-Meter.

The BTU-Meter operates as follows:

1. Sensors measure the fluid flow rate and temperatures in the supply and return piping for the HVAC component.

2. The sensor outputs are used by an electronic computer to calculate the rate of heat input or output from the HVAC components.

3. The output of the electronic computer is routed to a display for viewing by the operator.

Application of BTU-Meters

Table A1 lists the characteristics to be considered when selecting a BTU-Meter for a wide range of potential Army applications. Recently, a number of commercial meters have appeared on the market, and various laboratories have

Table A1

Characteristics To Be Considered in the Selection of a BTU-Meter

Characteristic	Characteristic Needed for Army Applications
Cost	Unit should be low cost, particularly for measurements on small pipe sizes.
Pipe size	Unit must be capable of performing measurements for the pipe size of the intended application; potential Army applications range from 1 to 8 in.
Calibration	Unit should be factory-calibrated (no field-calibration should be required).
Sensor accessibility	Sensors which are susceptible to damage should be accessible for repair or replacement.
Accuracy	Flow sensors = 5% of nominal flow value Temperature sensor = 0.1°C from 0 to 100°C. Electronic computer = 1% for calculation of rate of heat transfer for Δ = 10°C or higher.
Temperature range	50 to 250°F (10 to 121°C).
Fluid compatibility	Must be compatible with fluid in pipe; for collector loop applications, compatibility with glycol solutions or silicone oil might be required.
Pressure drop	Pressure drop produced by sensors in pipes should be small (less than 0.1 psi).

begun to test these units.[11] However, most of these units were designed to measure hot water consumption and are restricted to use on small pipes (pipe diameters of about 1 inch). CERL found one manufacturer who listed specifications for a BTU-Meter which met most of the requirements listed in Table A1. The BTU-Meter from this manufacturer was used for the solar monitoring at the EM Barracks Building at Fort Hood.

Figure A3 shows the measurement concept for the application at the EM Barracks Building. One BTU-Meter is located on the water side of the solar heat exchanger and measures the heat output of the solar collectors. A second

[11] Federal Solar Flares No. 3 (National Aeronautics and Space Administration [NASA], 1981); and Gerald R. Guinn and Leigh Hummer, Testing and Evaluation of Btu (Heat) Meters for Measuring Solar System Performance, Workshop on Performance Monitoring of Solar Domestic Hot Water Systems, Cape Canaveral, FL (December 1980).

BTU-Meter is located on the solar storage tank and measures the amount of DHW heating provided by solar. The second BTU-Meter also registers and displays the volume of DHW usage in gallons.

Although the application example given here is for a relatively simple HVAC system, more complex HVAC systems also can be monitored with BTU-Meters. This technique allows monitoring to be conducted at lower cost when the detailed, hour-by-hour evaluation provided by computer-based monitoring is not required.

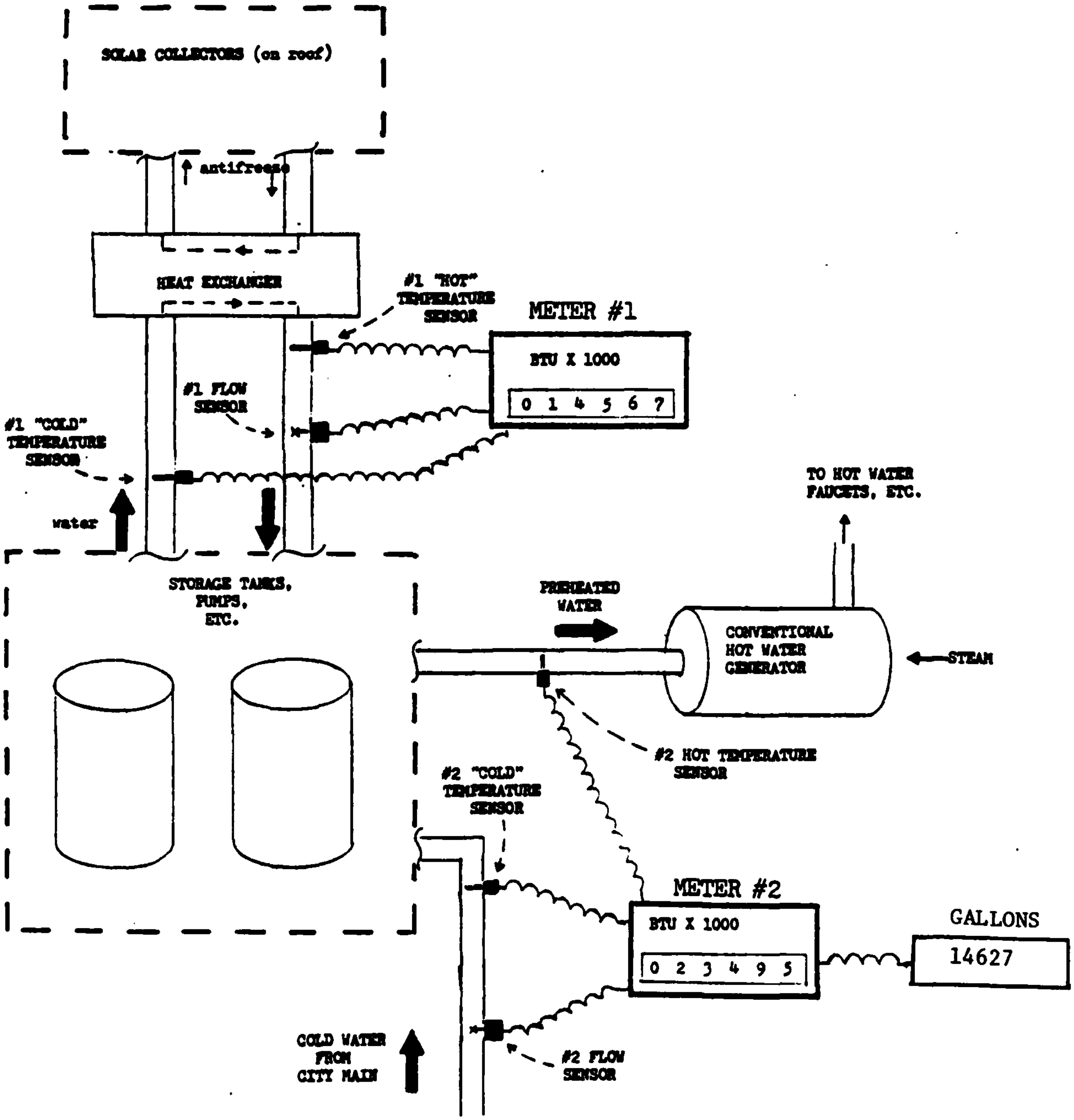

Figure A3. Measurement concept for monitoring at EM Barracks Building at Fort Hood.

METRIC CONVERSIONS

1 in.	= 25.4 mm
1 sq ft	= 0.092 m^2
1 cu ft	= 0.028 m^3
1 gal	= 3.7 L
1 kBtu	$=10^3$ Btu = 1.055 x 10^6 joules
1 kBtu/ft^2	=1.147 x 10^7 joules/m^2
1 °F-hr-ft^2/Btu	=176 °C-m^2/kW
1 °F	=(°C x 9/5) + 32
1 kWh	= 3.6 x 10^6 joules
1 MW	= 10^6 watts = 10^6 joules/sec
1 psi	= 6.895 x 10^3 newtons/m^2

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