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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION/-
FINAL REPORT FOR HONEYWELL OTS 45
SALT RIVER PROJECT, PHOENIX, ARIZONA

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Prepared by

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National Aeronautics and Space Administration
George C. Marshall Space Flight Center, Alabama 35812

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For the U.S. Department of Energy

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Solar Energy

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16. ABSTRACT This report has been developed for the Department of Energy as part of the Solar Heating and Cooling Development Program. It is one of a series of reports describing the operational and thermal performance of a variety of solar systems installed in Operational Test Sites under this program. It describes the operation and technical performance of the Solar Operational Test Site (OTS 45) at Salt River Project in Phoenix, Arizona, based on the analysis of data collected between April 1981 and March 31, 1982. The following topics are discussed: system description, performance assessment, operating energy, energy savings, system maintenance, and conclusions. The solar energy system at OTS 45 is a hydronic heating and cooling system consisting of 8208 square feet of liquid-cooled flat-plate collectors; a 2500-gallon thermal storage tank; two 25-ton capacity organic Rankine-cycle-engine-assisted water chillers; a forced-draft cooling tower; and associated piping, pumps, valves, controls and heat rejection equipment. The solar system has eight basic modes of operation and several combination modes. The system operation is controlled automatically by a Honeywell-designed microprocessor-based control system, which also provides diagnostics. Based on the instrumented test data monitored and collected during the 8 months of the Operational Test Period, the solar system collected 1143 MMBtu of thermal energy of the total incident solar energy of 3440 MMBtu and provided 241 MMBtu for cooling and 64 MMBtu for heating. The projected net annual electrical energy savings due to the solar system was approximately 40,000 kWh(e).			
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FOREWORD

This report has been developed for the Department of Energy as a part of the Solar Heating and Cooling Development Program. It describes the operation and technical performance of the Solar Operational Test Site (OTS) at Salt River in Phoenix, Arizona, and evaluates how the OTS has been functioning throughout a specified period of time, based on the analysis of data collected by the Site Data Acquisition System (SDAS). The objectives of the analysis are to report the long-term performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The contents of this document have been divided into the following topics of discussion:

- System Description.
- Performance Assessment.
- Operating Energy.
- Energy Savings.
- Maintenance.
- Summary and Conclusions.

Data used for the analysis have been collected, processed and maintained under the National Solar Data Network program, and were the major inputs used to perform the long-term technical assessment. The data have been archived by Automation Industries Inc., Vitro Laboratories Division, Silver Springs, Maryland.

SYSTEM HISTORY

In July 1976, Honeywell Energy Resources Center (Minneapolis, Minnesota) entered into a contractual agreement with NASA's Marshall Space Flight Center to design and develop solar-powered building space heating and cooling systems. This on-going engineering field test effort is known as the "404" program. The objective of the program was to develop, install and test solar heating and cooling systems that (1) exhibit efficient performance capabilities, (2) were low in cost, and (3) were modular in composition to enhance application.

Honeywell was the prime contractor for the program team. Barber-Nichols Engineering of Denver, Colorado, and Lennox Industries of Marshalltown, Iowa, were subcontractors. Honeywell was responsible for the solar system design, overall program management and subcontractor coordination. Barber-Nichols and Lennox worked as a team to develop solar-powered Rankine engine/air conditioner subsystems. Lennox Industries supplied HVAC products suitable for application in the system, including the production flat-plate solar collector. Data acquisition and reduction was done by IBM, Inc., and Vitro Laboratories.

The Salt River Project's (SRP) Crosscut Operation and Maintenance Building located in Phoenix, Arizona, was chosen as an Operational Test Site (OTS) for this program. The building contains offices, repair shops and warehouse facilities used to support the repair and maintenance of electrical equipment. The solar-powered heating and cooling system installed in the spring of 1981 provides solar heating only for the maintenance and repair shop and solar cooling only for the office space of the complex. The solar system made operational in May 1981 was designed to provide 89 percent of the required space heating and a maximum of 15.9 percent of the required space cooling. Additional heating and cooling is provided by the existing radiant heaters and the existing 228-ton Westinghouse centrifugal chiller, respectively.

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SECTION 1.0
SYSTEM DESCRIPTION

The Salt River Project Operational Test Site 45 (SRP OTS No. 45) is a solar heating and cooling system installed at the SRP's Crosscut Operation and Maintenance Building at Phoenix, Arizona. The system was designed to provide space heating in the form of solar-heated water during the heating season and space cooling in the form of chilled water during the cooling season as determined by a manual seasonal changeover procedure. Automatic switchover provisions in the system logic control the active mode. Space heating is supplied to the maintenance shop from stored thermal energy delivered to three unit heaters located along the south wall of the shop. Space cooling is provided by two 25-ton-capacity solar-powered Rankine-engine-assisted water chillers, each of which employs an auxiliary electric motor for primary power. Both of these high-efficiency (90 percent) electric motors also function as electric power generators to convert excess collected thermal energy to electricity, which is provided to the power grid. Each 25-ton Rankine-engine-assisted chiller employs a clutch to disengage the compressor; this provides power generation capability.

The system (see Figure 1-1) is a single-loop, two-pipe solar-powered hydronic heating and cooling system composed of the following basic components:

- Lennox LSC18-1 flat-plate liquid-type solar collectors (456 collectors, 8208 square feet gross area);
- Two Barber-Nichols 25-ton Rankine-engine-assisted chillers with generating capability;
- A 2500-gallon storage tank;
- Microprocessor-based solar controls with diagnostics;

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Figure 1-1. Solar System Schematic

- Forced draft cooling tower and open sump; this separate cooling tower was selected to enhance performance through optimal sizing (with respect to this Rankine unit's demands) and control strategies.
- Three unit heaters.
- Associated piping, pumps and other equipment.

The collectors are rooftop mounted and are oriented 34° west of south at a 20° incline. This orientation was dictated by the orientation of the roof. Figure 1-2 shows the site layout of the building complex and collector array. The 456 collectors are arranged in a matrix of 6-by-2 arrays; each array is 19 collectors long by 2 high, for a gross collector area of 8208 square feet and a net area of 7022 square feet. The 125-ton cooling tower, waste heat purge unit, and required hydronic and control-related components also are rooftop mounted.

Figure 1-2. Salt River Project Site Layout

The mechanical equipment room at the mezzanine level houses the two 25-ton Rankine-engine-assisted water chillers, eight pumps, the expansion tank and the requisite hydronic and control-related components. The 2500-gallon storage tank is located at the warehouse floor level, 12 feet below the level of the mezzanine. The cooling tower is located above the office area, adjacent to the existing cooling tower and the mechanical room. Figures 1-3 and 1-4 show the SRP building and collector array.

1.1 SYSTEM FLOW SCHEMATIC

The SRP OTS No. 45 commercial installation is a single-loop, two-pipe solar-powered hydronic heating and cooling system. It is centered around a solar collector loop containing an antifreeze mixture of water and approximately 20 percent ethylene glycol by volume. The solar collector loop incorporates an additional storage thermal loop for heating mode operation and a building two-pipe chilled water loop, which interfaces with the existing chilled water loop. The four main piping loops are (refer to Figure 1-1):

- Solar collector loop,
- Thermal storage loop,
- Chilled water loops, and
- Condenser water loops.

The overall system is in either a heating mode, a cooling mode, or an electric power generating mode, as determined by load demand. Within these three functions, eight discrete modes of operation and many combinations of these modes are possible, as detailed in Subsection 1.2, "System Modes of Operation."

Figure 1-3. Photograph of SRP Building Showing Front View of Rooftop Collectors

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1-6

Figure 1-4. Photograph of SRP Building Showing Back View of Collectors, Cooling Tower, and Purge Unit

1.1.1 Solar Collector Loop

The solar collector loop performs two functions: it provides hot solar fluid to the two Rankine engine boilers or it provides hot solar fluid to the storage tank via a storage charging bypass. This water/glycol loop, depicted by darkened lines on Figure 1-5, contains the following components:

- Solar collectors;
- Pump P6, which provides flow circulation;
- Pump P7, which serves as a backup for pump P6;
- Two Rankine engine boilers;
- The purge unit, which dissipates excess collected solar energy;
- Control valve V1, which acts as a proportional purge valve directing flow through the purge unit as necessary for dissipation of excess solar energy;
- Control valve V2, which directs flow either through the Rankine engine or to the storage tank;
- The solar collector loop expansion tank, which rectifies changes in pressure due to expansion and contraction of the working fluid with change in temperature;
- Pressure relief valves (PRV's)--one located near the air separator and one located on each row of solar collectors--which protect the system against excessive pressures in the event of pump failure and high solar insolation. The PRV near the storage tank normally will relieve

first due to the vertical "head" in the system. The discharge from this PRV is piped into a 55-gallon drum to retain system fluid for reuse.

1.1.2 Chilled Water Loops

These piping loops, shown in Figure 1-6, connect the Rankine chillers to the existing chilled water loop. Flow circulation is provided by pump P5.

1.1.3 Thermal Storage and Space Heat Loops

The storage charging piping (SS and SR) enables the transfer of collected energy into the 2500-gallon storage tank, with flow provided by pump P6. The space heat piping loop enables the transfer of stored energy in the tank to the three unit space heaters in the maintenance shop, with flow provided by pump P8. See Figure 1-7 for both loops.

1.1.4 Condenser Water Loops

The condenser water loops interface with the system chillers and Rankine engines. They contain the following components (as shown in Figure 1-8):

- 125-ton cooling tower,
- Condenser water pumps P9 through P12.

1.2 SYSTEM MODES OF OPERATION

The solar heating and cooling system provides heating in the form of solar-heated water, cooling in the form of chilled water or generation of electric power as determined by load demand, solar energy availability and storage tank status.

Figure 1-6. Chilled Water Loops and Interconnection with the Existing Loop

Figure 1-7. Thermal Storage and Space Heat Loops

Figure 1-8. Condenser Water Loop

To accomplish these three major functions of system operation, eight discrete modes of operation are possible:

- Mode 1--Storage Charging. The thermal storage tank is charged with thermal energy available from the solar collector field.
- Mode 2--Heating from Storage. Thermal energy stored in the thermal storage tank is used for heating.
- Mode 3--Solar Cooling. Chilled water is supplied from the Rankine chillers using the solar-powered Rankine engine to download the drive power required from the auxiliary electric motor.
- Mode 4--Auxiliary Cooling. Chilled water is supplied from the Rankine chillers using the auxiliary electric motor for drive power.
- Mode 5--Building Cooling. Chilled water is supplied from the existing chiller.
- Mode 6--Generation. Electric power is generated using the solar-powered Rankine engine to drive the auxiliary electric motor as a generator during the heating or cooling season.
- Mode 7--Purge. The purge unit is operated to reject excess heat to the ambient air to protect against overtemperature conditions in the collector fluid loop.
- Mode 8--Freeze Protection. The thermal storage fluid loop is operated to protect the system from effects of near-freezing ambient conditions.

Combinations of these modes can occur simultaneously as shown in Table 1-1. All system modes of operation are controlled automatically by the solar control panel, the Rankine control panel and the existing building air

Table 1-1. Combination Modes

MODE	COMBINATIONS	MODE	COMBINATIONS
1A	1 2	2G	2 6
1B	1 2 4	2H	2 8
1C	1 2 4 5	3A	3 4
1D	1 4	3B	3 4 5
1E	1 4 5	3C	3 5
2A	2 3	3D	3 5 7
2B	2 3 4	3E	3 6
2C	2 3 4 5	3F	3 6 7
2D	2 3 5	3G	3 7
2E	2 4	4A	4 5
2F	2 4 5	6A	6 7

conditioning control panel. The solar control panel takes inputs from the various sensors, flow switches and space thermostats in the system and, through microprocessor logic, places the solar heating and cooling system into the most appropriate mode of operation--heat, cool or generate. In the event that a chiller or Rankine engine is called but has failed, the controller will initiate the next priority mode. This ensures the optimal use of solar energy. Figure 1-9 shows the location of all control sensors and the SDAS sensors in the system.

Prioritization of the system modes is effected through a command seasonal selector switch, which defines discrete heating and cooling seasons. The season selector switch effectively locks out all storage during summer operation. During summer operation, solar energy is utilized to cool and then generate, whereas during winter operation, solar energy is utilized to heat, store, cool and then generate. Normally the switch is set for heating season operation from November 1 through March 15 and for cooling season operation from March 16 through October 31, although the switch may be manually reset at any time.

△ EP507 SAME AS EP511, EP508 SAME AS EP512

Figure 1-9. Location of Control Sensors

Table 1-2 summarizes the system response to calls for various discrete modes. A detailed explanation of all system modes of operation is given in the following subsections.

1.2.1 Heating Modes of Operation

By placing the season selector switch on the solar control panel to the WINTER position, the system automatically will be placed in the most appropriate mode of operation for the heating season according to demand. Cooling modes and combination modes involving cooling are possible during the heating season; thus, solar energy will be utilized to heat, cool and then generate according to demand.

When solar energy is available, the system's first priority is to supply hot solar fluid to the storage tank from the collectors to satisfy any potential heating demand. If the system receives a heating command (when the thermostat in the maintenance shop calls for heat) and if solar energy is available from the storage tank, it will be supplied directly to the load. When solar energy is available and a heating demand exists at the same time, both heating and storage charging occur simultaneously. Any cooling demands will be satisfied as a second priority, utilizing direct solar energy whenever possible to minimize the use of auxiliary conventional energy.

During periods of high solar insolation and low heating demand, when the storage tank is fully charged, the generation mode will be activated as a third priority. If solar energy is not available from the storage tank (which can provide 8 hours of heating when fully charged), the heating load cannot be satisfied. The system is designed to provide 89 percent of the seasonal heating requirements. No auxiliary heat is provided.

1.2.1.1 Storage Charging (Mode 1)--The system configuration and flow diagram for this mode are shown in Figure 1-10. If the collector plate temperature T_{Pl} exceeds 140°F and exceeds the storage tank temperature by 5°F , and

Table 1-2. Summary of System Responses to Operational Modes

LEAD UNIT	SUMMER/WINTER	MODE OF OPERATION	EQUIPMENT STATUS MODE OF OPERATION	PUMP 1	PUMP 2	PUMP 3	PUMP 4	PUMP 5	P6 OR P7	PUMP 8	PUMP 9	PUMP 10	PUMP 11	PUMP 12	UNIT 1		UNIT 2		V1		V2		PURGE FAN	TOWER FAN 1	TOWER FAN 2	WESTINGHOUSE	UNIT HEATER
															AC	RE	AC	RE	A-AB	B-AB	A-AB	B-AB					
-	W	1	STORAGE	-	-	-	-	-	1	-	0	-	0	-	-	0	-	0	-	-	-	1	0	0	-	-	-
-	W	2	HEATING FROM STORAGE	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	0	1	-	-	-	-	1
1	E	3	SOLAR COOLING	-	-	1	1	1	1	0	1	1	0	0	1	1	0	0	-	-	0	1	0	2	2	0	-
2	E	3	SOLAR COOLING	-	-	1	1	1	1	0	0	0	1	1	0	0	1	1	-	-	0	1	0	2	2	0	-
B	E	3	SOLAR COOLING	-	-	1	1	1	1	0	1	1	1	1	1	1	1	1	-	-	0	1	0	2	2	0	-
1	E	4	AUXILIARY COOLING	-	-	1	1	1	0	-	0	1	0	0	1	0	0	0	-	-	0	1	0	2	2	0	-
2	E	4	AUXILIARY COOLING	-	-	1	1	1	0	1	0	0	0	1	0	0	1	0	-	-	0	1	0	2	2	0	-
B	E	4	AUXILIARY COOLING	-	-	1	1	1	0	-	0	1	0	1	1	0	1	0	-	-	0	1	0	2	2	0	-
-	E	5	BUILDING COOLING	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	0	1	-	-	-	1	-
1	E	6	GENERATE	-	-	-	-	0	1	-	1	0	0	0	0	1	0	0	-	-	0	1	-	2	2	-	-
2	E	6	GENERATE	-	-	-	-	0	1	-	0	0	1	0	0	0	0	1	-	-	0	1	-	2	2	-	-
B	E	6	GENERATE	-	-	-	-	0	1	-	1	0	1	0	0	1	0	1	-	-	0	1	-	2	2	-	-
-	E	7	PURGE	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	0	1	0	1	1	-	-	-	-
-	E	8	FREEZE PROTECTION	-	-	-	-	-	1	-	0	-	0	-	-	0	-	0	1	0	0	1	0	-	-	-	-

LEGEND:

- 1 = ON.
- 2 = ON IF REQUIRED TO MAINTAIN CONDENSING TEMPERATURE.
- W = WINTER.
- E = EITHER SUMMER OR WINTER.
- B = BOTH RANKINES 1 AND 2.
- = NOT APPLICABLE TO THIS MODE.

Figure 1-10. Storage Charging Mode

if the storage tank temperature TS1 is less than 190°F, then the storage charging mode is activated. Solar loop pump P6 is activated. Control valve V2 is positioned A to AB to direct hot solar fluid through the storage tank. Storage charging continues until the temperature difference between TP1 and TS1 falls to 0 F°, or until the storage tank temperature exceeds 190°F, at which point the storage tank is fully charged.

1.2.1.2 Heating (Mode 2)--The system configuration and flow diagram for this mode are shown in Figure 1-11. When a heating command exists from thermostat T1 and the storage tank temperature at sensor TS1 is greater than 140°F, heat is supplied directly to the load from the storage tank. Pump P8 is activated to provide circulation of hot solar fluid to the maintenance shop. Heating from storage continues until the heating demand has been satisfied or until the storage tank temperature falls below 135°F.

1.2.2 Cooling Modes of Operation

By placing the season selector switch on the solar control panel to the SUMMER position, all heating modes and combination modes involving heating are locked out and the system will be placed automatically into the proper mode of cooling operation according to demand.

When a cooling demand exists from the building control panel, the chillers are placed into automatic operation. The auxiliary electric motors and capacity control are determined by the solar control panel microprocessor and chilled water sensor TW1. Cooling capacity control is effected in five stages: first half lead machine, second half lead machine, first half lag machine, second half lag machine, and finally the existing Westinghouse chiller is authorized. The lead/lag switch determines which chiller starts first, although the normal position has chiller 1 leading.

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Figure 1-11. Heating, Mode 2

When solar energy is available during the cooling mode of operation, the solar collectors supply hot solar fluid to the lead Rankine engine, which is utilized to unload the electric motor of the lead chiller. If both chillers are operating and sufficient solar energy is available, both Rankine engines will unload simultaneously. If more than sufficient solar energy is available to meet low cooling demands (only one chiller has been authorized), the system will provide cooling and generation simultaneously. If no cooling demand exists, the system will generate.

On a call for cooling from the existing space thermostats located in the office area, the cooling tower can operate at low speed or high speed, as determined by temperature sensor TT1. Sensor TT1 energizes the cooling tower fan for low-speed operation if the condenser water temperature rises above 80°F (adjustable). Sensor TT1 energizes the fan for high-speed operation if the condenser water temperature rises above 85°F (adjustable).

1.2.2.1 Solar Cooling (Mode 3)--The configuration and flow scheme for this mode are shown in Figure 1-12. When chiller 1 is operating, the system will attempt to operate the Rankine engine section, utilizing direct solar energy from the collectors to download the drive required from the auxiliary electric motor. If the solar loop temperature TL1 is greater than 155°F and pump P6 is operating as determined by flow sensor FL1, then the lead Rankine engine and condenser water pump P9 will be energized. If sensor TL1 exceeds 170°F and the lag chiller is operating, then the lag engine and condenser water pump P11 will be energized. During Rankine engine operation, the auxiliary electric motor remains energized and is unloaded as the Rankine engine comes up to speed. If the cooling demand is light and the output power of the Rankine engine is greater than that required by the compressor, the auxiliary electric motor will act as an electric generator, feeding power back into the electrical system. Direct cooling from one or both Rankine engines will continue until the cooling demand has been satisfied or the solar loop temperature as sensed by TL1 has fallen below 145°F and 160°F, respectively.

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Figure 1-12. Cooling, Mode 3

1.2.2.2 Auxiliary Cooling (Mode 4)--The configuration and flow diagram for this mode are shown in Figure 1-13. In response to a cooling demand from the building control panel, chiller No. 1 (lead unit) will be activated and will unload as required to maintain a 46°F chilled water temperature. Pump P5 and the existing chilled water pumps P3 and P4 are energized. Chiller No. 2 (lag unit) will be activated whenever the lead chiller is operating at full capacity. Associated condenser pump P12 is energized with chiller No. 2.

1.2.2.3 Building Cooling (Mode 5)--The existing building chiller will operate if the cooling load exceeds the capacity of the solar system chillers. Thus, Mode 5 will not appear as a discrete mode except during equipment failures. Authorization of the building chiller is automatic and determined by the microprocessor when the chilled water temperature sensor TW2 exceeds 48°F. Capacity control for the Westinghouse chiller is effected by its existing controls.

1.2.3 Generation Modes of Operation

When solar energy is available, Rankine-engine electric power generation can occur during four normally anticipated conditions:

1. The system is in wintertime service, no heating demand exists and the storage tank is fully charged;
2. The system is in wintertime service and the heating demand can be satisfied with available solar energy from the fully charged storage tank;
3. The system is in summertime service and no cooling demand exists;
4. The system is in summertime service and the cooling demand can be satisfied by the output of just one chiller.

Figure 1-13. Auxiliary Cooling, Mode 4

Under the first three conditions, the lead Rankine engine will generate if excess solar energy is sufficient to power one Rankine unit, and both Rankine engines will generate if excess solar energy is sufficient to power two units. Electric power generation will occur for the fourth condition when available solar energy is sufficient to operate both Rankine units; the lead Rankine engine will be used to generate electrical energy.

The first and third conditions are described in detail below. The second and fourth conditions are combination modes.

1.2.3.1 Electric Power Generation During Wintertime Service (Mode 6)--The system configuration and flow diagram for this mode are shown in Figure 1-14. During the heating season, when no call for heating exists, the lead Rankine engine and pump P6 are activated for the generation mode if the plate temperature at TP1 exceeds 140°F, the storage tank temperature is greater than 190°F as determined by sensor TS1, and the solar loop temperature as sensed by TL1 exceeds 155°F. The electric clutch is activated by logic in the Rankine control panel to decouple the water chiller compressor; this allows the Rankine engine to drive the auxiliary motor as a generator. If the available solar energy is sufficient to operate both Rankine engines, as indicated by TL1 exceeding 170°F, then the lag unit also will generate. Condenser pumps P9 and P11 will be activated with their respective Rankine engines. Electric power generation by one or both Rankine units will continue until one of the following conditions occurs: the solar loop temperature drops below 145°F or 160°F, respectively; the storage tank temperature falls below 190°F; or a heating or cooling demand occurs.

1.2.3.2 Electric Power Generation During Summertime Service (Mode 6)--The configuration and flow schematic for this mode also are shown in Figure 1-14. When no call for cooling is present during the cooling season, then the generation mode is activated if the solar loop temperature at sensor TL1 is greater than 155°F and the plate temperature at sensor TP1 exceeds 140°F. Solar pump P6 and associated condenser pumps P9 and P11 also are activated.

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Figure 1-14. Electric Power Generation

1.2.4 Protection Modes of Operation

1.2.4.1 Purge (Mode 7)--For overtemperature protection during any mode of operation, the system will purge excess energy. Collector loop temperature sensor TL2 is used to control valve V1 such that the loop temperature normally is at or below 220°F. Normally, valve V1 will be set A to AB. At 210°F, valve V1 will modulate toward B to AB; at 220°F, valve V1 will be fully B to AB. At 20 percent valve movement toward B to AB, pneumatic-electric relay PE1 will trip to start the purge fan via the microprocessor. PE1 will open at 100 percent valve movement to stop the purge fan. During failure of the Rankine engines, additional energy can be purged by manually switching valve V2 to A to AB.

1.2.4.2 Freeze Protection (Mode 8)--The flow diagram for this mode is shown in Figure 1-15. If the collector temperature as sensed by TP1 falls below 25°F, pump P6 is operated, and valve V2 is positioned B to AB such that solar fluid is circulated to prevent freezing of the collector field.

1.3 TYPICAL SYSTEM OPERATION AND OPERATING SEQUENCE

Normally, the system at SRP is set for winter operation from November 1 through March 15 and for summer operation from March 16 through October 31. Setting the SUMMER/WINTER switch in the SUMMER position disables all heating and combination modes involving heating. The system does not charge or discharge thermal storage in the summer. Typical system operation and the operating sequence for summer and winter operations are described below.

1.3.1 Summer Operation

Figure 1-16 presents the bar chart illustrating the system operating sequence on a typical clear day during the cooling season (June 17, 1981). Solar energy was used to cool the building between 0930 hours and 1800 hours. The

Figure 1-15. Freeze Protection, Mode 8 (Darkened Lines)

Figure 1-16. Typical Cooling Season Operating Sequence (June 17, 1981)

building cooling demand on this day was high and existing Westinghouse chillers (228 tons) were operating all the time. Both system chillers (25 tons each) were operating at full capacity; this was typical of operation during the summer because the Rankine engine chillers at design contribute only a small portion of the total building load. There was no power generation. The collector pump cycled two times before coming on for continuous operation between 0930 and 1800 hours. The Rankine-cycle air conditioning system was in the auxiliary cooling mode between 0500 hours and 0930 hours, in the solar assisted cooling mode between 0930 and 1800 hours and in the auxiliary cooling mode from 1800 hours to 2300 hours.

Figures 1-17 and 1-18 show the solar system operation profile and the conditions at various points in the system throughout the day on June 17, 1981. Figure 1-17 shows the instantaneous values of incident solar insolation, the collector inlet and outlet temperatures and associated events. The solar circulating pump cycled two times before turning on at 0930 hours for continuous operation until shutdown at 1800 hours. There was no cycling during shutdown. When the system initially turned on, the solar insolation level was about 140 Btu/hr-ft², which was typical of clear days in June. The total energy incident on the collector field before the system turned on was approximately 1.7 MMBtu. The total operational energy¹ was 83 percent of the total incident energy.² The solar fluid temperature at the collector outlet reached a peak of 197°F at about 1330 hours; this corresponds to the peak insolation level. The collector outlet temperature remained significantly above the inlet temperature during the system operating period.

¹Total operational energy is the total energy striking the collector field when the collector loop pump operates.

²Total incident energy is the total energy striking the collector field, independent of system operation.

Figure 1-17. Solar Insolation and Collector Fluid Temperature versus Time of Day (June 17, 1981)

Figure 1-18. System Operation Versus Time of Day (June 17, 1981)

Figure 1-18 shows conditions at various points in the subsystems affected by the cooling mode of operation. Figure 1-18a shows the solar system operation profile (same as Figure 1-17). The inlet and outlet temperatures to the two Rankines and their operating times are shown in Figures 1-18b and 1-18c. Rankine unit No. 2 came on when the solar fluid temperature was about 150°F, as expected, and Rankine unit No.1 came on when the temperature was about 170°F. These were the preset control temperatures for Rankine operation. Rankine unit No. 1 operated from 1000 to 1800 hours and Rankine unit No. 2 operated from 0930 to 1700 hours. Rankine unit No. 2 was the lead unit during start-up because Rankine unit No. 1 had start-up problems. The chiller compressors came on at 0500 and stayed on until 2300 hours as shown in Figure 1-18d. The temperature difference during operation across the chillers was about 7 to 8 F°. The cooling tower operation, condenser water temperature and ambient temperature are shown in Figure 1-18e. Cooling tower fan No. 1 came on at 0500 and stayed on until 2300 hours coincident with chiller operation. Tower fan No. 2 came on at 1000 hours when the condenser water temperature was about 80°F, which was the set point for fan No. 2 to start. The condenser water temperature increased during the day when both Rankine units were on. Fan No. 2 shut off when the condenser water temperature dropped below 75°F at 1700 hours, coincident with one of the Rankine units shutting down. The ambient air temperature increased during the day to a peak of 109°F at 1700 hours and then decreased.

1.3.2 Winter Operation

On most winter days the building at SRP requires both heating and cooling to maintain comfort. In the winter mode of operation, the solar system contributes to both heating and cooling demand. Priority is given to charging thermal storage to full capacity before meeting the cooling demand. The system operating sequence and system operation on December 15, 1981, exemplify these storage charging, cooling and space heating modes. Also, system operation under one of the Rankine failure modes was demonstrated on that day. The system operating sequence is presented in Figure 1-19.

Figure 1-19. Typical Heating Season Operating Sequence
(December 15, 1981)

On December 15, 1981, solar energy was used to charge storage between 1005 and 1400 hours until it was fully charged. Storage is considered fully charged when the storage fluid temperature is 190°F . The circulating pump was cycling between 1300 and 1400 hours. From 1400 hours to 1605 hours the solar fluid flow was directed through the Rankine boilers. Due to a Rankine unit No. 1 start-up problem, the purge unit was on from 1430 to 1505 hours. Rankine unit No. 1 came on at 1455 hours and continued to cool and generate until 1605. Auxiliary cooling was used intermittently from 0700 hours to 1930 hours. Space heating from thermal storage was used for about 6 hours between 0000 and 0710 hours.

The solar system operation and conditions at various points in the system throughout the day on December 15, 1981, are shown in Figures 1-20 through 1-22. Figure 1-20 shows the instantaneous values of solar insolation and the collector fluid inlet and outlet temperatures. The circulation pumps came on at 1005 hours when the fluid temperature was about 110°F (the set point for storage charging) and began charging storage. The solar insolation was 130 Btu/hr-ft^2 . The solar fluid temperature continued to increase until the storage was fully charged at a temperature of 190°F . Due to the Rankine unit No. 1 start-up problem and Rankine unit No. 2 motor-bearing problem, no thermal energy was removed from the system after storage was charged. Thus, the collector fluid temperature continued to rise until the purge unit was activated. Normally, after the storage is fully charged the collector fluid flow switches over to the Rankine boilers to either cool or generate. Rankine unit No. 1 was started manually at 1455 hours as indicated by the sharp decrease in collector fluid temperature in Figure 1-20.

Figure 1-21 shows the instantaneous values of temperatures in the storage tank, in the storage charge loop, and in the storage discharge loop. The approximate location of the sensors also is shown. During heating from storage, the storage fluid temperature and the hot fluid return temperature from the space heaters decreased continually. Temperature sensor T201 showed a decrease even after the storage heating pump was shut off and showed a

SITE: OTS NO. 45 (SRP, PHOENIX, AZ)
DATE: DECEMBER 15, 1981

Figure 1-20. Typical Clear Day Solar System Operation in Winter
(December 15, 1981)

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SITE: OTS NO. 45 (SRP, PHOENIX, AZ)
DATE: DECEMBER 15, 1981

Figure 1-21. Typical Thermal Storage Operation (December 15, 1981)

Figure 1-22. Rankine Unit Operation (December 15, 1981)

sudden drop when the charge mode was commenced. The sudden drop was caused when a cold slug of fluid sitting in the piping overnight reached sensor T201. During charging, the readings on all three tank sensors were the same; this indicated a well-mixed condition. The tank was fully charged at 1330 hours when the storage temperature was 190°F.

Figure 1-22 shows the instantaneous values of temperatures at the boiler inlet and outlet of Rankine unit No. 1. Upon a call for cooling, collector fluid was directed through the Rankine unit No. 1 boiler at 1400 hours. The solar fluid temperature was 190°F. The Rankine engine did not start automatically as mentioned previously, but was started manually at 1455 hours. A rise in solar fluid temperature as measured at Rankine boiler inlet sensor T560 before 1400 hours may be attributed to a slow leak in the three-way valve. The temperature drop was typically 13 F° across the Rankine boiler when the engine was operational.

Figure 1-23 shows the instantaneous values of solar insolation and collector fluid inlet and outlet temperatures for a typical partly cloudy day in December (December 22, 1981). The bar chart at the bottom of the figure shows that the collector pump cycled on and off several times. The storage was in a fully charged state and the solar fluid flow was directed through the Rankine boilers.

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Figure 1-23. Typical Partly Cloudy Day Solar System Operation in Winter
(December 22, 1981)

SECTION 2.0
PERFORMANCE ASSESSMENT

The Operational Test Period (OTP) for the SRP solar heating and cooling system extended from April 1, 1981, to March 31, 1982.¹ During this time data was gathered and processed through the National Solar Data Program. System performance assessments made in this section are based on the analysis of the data collected at the end of the OTP.

The performance assessment for the OTP is made from two perspectives:

- Overall system performance is assessed. The total solar energy available, the system load, and the system solar fraction are presented.
- An in-depth evaluation is made of the performance of the following individual subsystems:
 - Collectors.
 - Storage.
 - Space Heating.
 - Space Cooling.
 - Rankine-cycle air conditioner.

All performance parameters presented in this report conform to the definitions used by the National Solar Data Program for its monthly performance reports [1]; additional parameters have been presented to provide further insight into the performance of this system and its subsystems. The definitions of all performance parameters used in this report are listed in Appendix A. Appendix B contains the equations that were used to calculate the

¹Performance during April, May, and November 1981 and March 1982 is not reported because sufficient measured data was not available due to either system problems or site data acquisition problems. During other months when SDAS problems were encountered estimates were based on data collected during the month.

the performance parameters from the raw data collected from the site. Appendix C lists the sensors used to monitor the performance of the system; shows the locations within the system of all sensors; and describes the data collection, retrieval and reduction methods.

Instrumentation accuracies are affected by sampling error and by systematic sensor errors due to inaccurate calibration, drift and nonlinearities. To evaluate the effect of sensor errors on the performance factors, an error analysis was conducted and is presented in Appendix D. The performance factors presented in this document should be viewed in light of this uncertainty in measurement.

2.1 SYSTEM PERFORMANCE

The solar energy system performance summarized in this section can be viewed as the dependent response of the system to certain primary inputs. These primary inputs are incident solar radiation, average ambient temperature and system load. Dependent system responses are the system solar fraction and total energy savings. The monthly values of these inputs and outputs measured during the operational period are shown in Table 2-1, along with long-term average values of daily incident solar energy and outdoor ambient temperature. A comparison of measured weather data to the long-term average may be used to indicate expected long-term performance of the system.

Figure 2-1 depicts utilization by the system of the total incident solar energy on the collectors during the OTP (excluding April, May, and November 1981 and March 1982). Of the total incident solar radiation (insolation), 80 percent fell on the collectors while the solar pump was active (operational incident energy). The system collected 42 percent of the operational incident solar energy. The collected energy either was delivered to thermal storage to provide for heating, delivered to the Rankine-cycle boilers to be used to generate power or to cool the building, purged (intentionally

Table 2-1. System Performance

MONTH	DAILY INCIDENT ENERGY PER UNIT AREA		AMBIENT TEMPERATURE		BUILDING LOAD (MEASURED)		SYSTEM LOAD (MEASURED)		SOLAR FRACTION OF THE SYSTEM LOAD		ELECTRICAL ENERGY SAVINGS [kWh(e)]
	(MEASURED) (Btu/FT ² -DAY)	(LONG-TERM AVERAGE) (Btu/FT ² -DAY)	(MEASURED) (°F)	(LONG-TERM AVERAGE) (°F)	HEATING (MMBtu)	COOLING (MMBtu)	HEATING (MMBtu)	COOLING ^(a) (MMBtu)	HEATING (PERCENT)	COOLING (PERCENT)	
JUNE 1981	2217	2567	93	84	0	700	0	227	-	26	2,872
JULY 1981	2058	2361	93	90	0	850	0	239	-	19	2,755
AUGUST 1981	2048	2306	93	88	0	774	0	211	-	19	2,520
SEPTEMBER 1981	1890	2153	87	82	0	625	0	240	-	16	1,934
OCTOBER 1981	1661	1806	72	72	0	329	0	191	-	17	1,758
NOVEMBER 1981	(b)	1493	(b)	59	(b)	(b)	(b)	(b)	(b)	(b)	(b)
DECEMBER 1981	1240	1155	57	52	16 ^(c)	63	16 ^(b)	43	100	15	4,630
JANUARY 1982	1171	1265	52	50	21	20	21	20 ^(c)	60	23	3,927
FEBRUARY 1982	1436	1639	59	55	36	58	36	58 ^(c)	50	25	5,804
TOTAL AVERAGE	1715	2093	76	72	73 24	3419 427	73 24	1229 154	64 ^(d)	19.6 ^(d)	26,200 3,275

(a) THE COOLING LOAD SUPPLIED BY THE RANKINE CHILLERS IN THE SOLAR-ASSIST AND AUXILIARY COOLING MODES.

(b) NOT AVAILABLE.

(c) ESTIMATED.

(d) WEIGHTED WITH LOAD.

Figure 2-1. System Test Period* Solar Energy Use

*Eight months of GTP (June, July, August, September, October, December, January, February)

rejected to environment), or lost to the environment. As shown in the figure, the greatest portion (81 percent) of collected energy was delivered to the Rankine boilers. Of this, 96 percent was used for cooling and 4 percent was used for generation. Collected energy delivered to thermal storage to provide for space heating accounted for 7 percent. Purged energy was estimated to be 4 percent of collected energy. Most of the energy purging occurred when one of the Rankine engines was inoperable. The system energy losses accounted for 8 percent of the energy collected. This includes piping heat losses and the thermal energy required each day to bring the system to operating temperatures.

2.2 SUBSYSTEM PERFORMANCE

This subsection presents the results of analyzing the monthly data available for the five subsystems--collector, storage, space heating, space cooling and Rankine-cycle air conditioner. Subsystem performance is evaluated by calculating a set of primary performance factors. The electrical energy required to operate pumps and fans to support each of these subsystems--while an important consideration in the overall performance of each subsystem--is not presented here but appears in Section 4.0.

2.2.1 Collector Performance

The most common measure of collector performance is collector efficiency, defined as the ratio of solar energy collected to total solar energy incident on the array (including the collector frames). Table 2-2 presents the average collector array performance for each month of the reporting period. The collector array efficiency listed in the table was based on total incident solar radiation, including incident solar radiation occurring when the array was not active. Thus, this efficiency was affected directly by system conditions (other than array performance), which determined the active periods of the collector array. The operational collector efficiency, on the other

Table 2-2. Collector Array Performance

MONTH	INCIDENT SOLAR ENERGY (MMBtu)	COLLECTED SOLAR ENERGY (MMBtu)	COLLECTOR ARRAY EFFICIENCY	OPERATIONAL INCIDENT ENERGY (MMBtu)	OPERATIONAL COLLECTOR EFFICIENCY	AMBIENT TEMPERATURE (°F)
JUNE 1981	547	219	0.40	477	0.46	93
JULY 1981	524	216	0.41	455	0.47	93
AUGUST 1981	521	206	0.40	457	0.45	93
SEPTEMBER 1981	457	152	0.33	399	0.38	87
OCTOBER 1981	423	118	0.28	332	0.36	72
NOVEMBER 1981	(a)	(a)	(a)	(a)	(a)	(a)
DECEMBER 1981	315	59	0.19	198	0.30	57
JANUARY 1982	299	64	0.21	179	0.36	52
FEBRUARY 1982	342	109	0.32	257	0.42	59
TOTAL	3438	1143	-	2754	-	-
AVERAGE	430	143	0.33	344	0.42	76

(a) NOT AVAILABLE.

hand, was based only on the solar energy incident upon the array when the array was active (collecting solar energy). This parameter therefore provides a clearer view of the average array performance during operation; it minimizes the effects of other system conditions.

The SRP collector array performed well; it collected 33 percent of all the solar energy incident upon it and 42 percent of the solar energy incident during collector operation. Based on the instrumentation error analysis presented in the collector efficiencies calculated from Appendix D, measured data have an uncertainty of ± 10.6 percent.

As indicated in Table 2-2, the operational incident energy and the operational collector efficiency were higher during the summer months. The ambient temperature is higher and the angle of sun's path above the horizon is higher in summer than winter; this results in a lower operating point as in summer months than in winter months.

Collector efficiency is inversely dependent upon the operating point, which is defined as:

$$X_j = \frac{T_i - T_a}{I}$$

where

- X_j = collector operating point at the j th instant,
- T_i = collector inlet temperature,
- T_a = ambient temperature, and
- I = insolation.

Therefore, during the summer months when ambient temperature and peak insolation are comparatively high, the value of the operating point is

comparatively low and collector efficiency is comparatively high. The typical operating point around noon during summer was about 0.25 whereas during winter it was about 0.35.

The inverse dependency of collector efficiency on the operating point is depicted in Figure 2-2. The figure also illustrates the measured and expected array performance. The performance curves are all based on gross collector area and include:

- The performance of a single collector panel before and after a long-term weathering test consisting of 15-1/2 months of stagnation and exposure to the environment[2].
- Measured collector array data, calculated as the energy gain of fluid passing through the collectors divided by solar insolation striking the gross collector area during system operation. All points for calculation of measured collector efficiency were taken within +2 hours of noon.

As shown, the measured performance of the array was close to the performance of a single panel after prolonged stagnation conditions.

2.2.2 Storage Performance

The storage tank is a 2500-gallon steel tank with a 5/8-inch corrosion-resistant lining. The tank is filled with 2400 gallons of 20-percent ethylene glycol-water mixture with Dowtherm® SR-1 added as a corrosion inhibitor. The tank is located inside the building and is enclosed by a plywood partition filled with rockwool insulation.

Figure 2-2. Inverse Dependency of Collector Efficiency on Operating Point

Table 2-3 lists the storage subsystem performance parameters for each month of the test period. Energy to storage is the total solar energy delivered to the storage subsystem by the collector subsystem. Energy from storage is the total solar energy transferred from the storage subsystem to the load subsystems. Storage efficiency is a measure of the portion of the energy delivered to storage that was delivered to the load subsystems or resulted in a change in stored energy.

During the summer months (April to late October), storage is not used. However, Table 2-3 shows a small amount of energy being charged to storage in August 1981. This small amount of energy to storage was due to an apparent leak in the three-way valve.

The storage heat loss coefficient calculated using summer data shows a consistent value of $0.1 \text{ Btu/hr-ft}^2\text{-F}^\circ$. During the winter months (December to February) 73 MMBtu of collected energy was charged to storage and 46 MMBtu of stored energy was discharged from storage to be used for space heating. The change in stored energy in these months was an increase of 1 MMBtu. The heat loss coefficient calculated based on tank surface area in winter is higher than that in summer. This is because in winter the heat loss from the pipes leading to and from the storage tank is high.

The energy charged to storage was lower than the expected 150 MMBtu in December, January and February because the minimum set point temperature for storage charging was increased from 110°F to 140°F with the maximum remaining at 190°F . This change was necessitated because the air being discharged from the unit heaters was uncomfortably cool to the personnel when the storage temperature was below 140°F .

2.2.3 Space Heating Performance

Solar heating is provided from thermal storage by pumping ethylene glycol-water (the storage medium) through unit heaters (water-to-air heat exchangers).

Table 2-3. Storage Performance

MONTH	ENERGY TO STORAGE (MMBtu)	ENERGY FROM STORAGE (MMBtu)	CHANGE IN STORED ENERGY (MMBtu)	STORAGE EFFICIENCY	STORAGE AVERAGE TEMPERATURE (°F)	EFFECTIVE STORAGE HEAT LOSS COEFFICIENT (Btu/HR-FT ² -F)	STORAGE TEMPERATURE, DAY 1	STORAGE TEMPERATURE, DAY 30
JUNE 1981	0	0	-0.39	-	124	0.10	143	112
JULY 1981	0	0	-0.23	-	101	0.11	112	97
AUGUST 1981	0.51	0	0.31	-	95	0.10	97	114
SEPTEMBER 1981	0	0	-0.28	-	99	0.12	110	93
OCTOBER 1981	1.94	0.46	1.51	1.00	92	0.07	92	171
NOVEMBER 1981	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
DECEMBER 1981	28.60	16.16	0.78	0.60	172	0.46	170	180
JANUARY 1982	18.00	12.47	0.34	0.71	173	0.27	180	188
FEBRUARY 1982	26.50	17.72	-0.10	0.67	175	0.37	188	180
TOTAL AVERAGE ^(b)	75.5 24.3	46.81 15.3	1.93 0.33	- 0.64	- -	- 0.20	-	-

(a) NOT AVAILABLE.

(b) MONTHLY AVERAGE FOR WINTER MONTHS ONLY (DECEMBER, JANUARY AND FEBRUARY).

The performance parameters for the space heating subsystem for the test period are listed in Table 2-4. The solar system provided 47 MMBtu of heating over the three-month period. The system heating load in December was not available because the sensors on the radiant heaters were wired incorrectly until late January 1982.

When the fluid temperature in the hot water supply line was lower than 140°F, temperature of the air from unit heaters was at an uncomfortably low level. Therefore, most of the time during the heating season the blowers were manually turned off when this condition occurred. The minimum set point for storage charging and discharging was adjusted upwards from 110°F to 140°F. This resulted in a reduction in the heat storage capacity and a reduction in the amount of heating supplied from solar sources.

2.2.4 Space Cooling Performance

The space cooling subsystem consists of the two 25-ton Rankine engine air conditioners (R/C-A/C) and an existing 228-ton Westinghouse chiller. The Rankine units use solar energy when available; otherwise they use auxiliary electrical energy. The conventional chillers use only electrical energy and are used if the Rankine units cannot meet the cooling demand. The solar system was designed to provide 100 percent of the shaft power needed by the system with 195°F solar water temperature and 85°F condenser water temperature. Performance of the Rankine units is discussed in the following section.

Measured monthly performance parameters for the space cooling subsystem are listed in Table 2-5. The significant cooling load in Phoenix occurs between May and October. Data for the month of May were not available because the SDAS was not operational most of the time during the month. June 1981 is taken as an example for discussion. The measured building load was 704 MMBtu and the Rankine chillers supplied 230 MMBtu. The calculated solar portion of the cooling supplied from the Rankine units was 60 MMBtu. This represents a solar fraction of 26 percent of the total cooling produced by Rankine chillers or 8.5 percent of the building load.

Table 2-4. Space Heating Subsystem Performance

MONTH	SPACE HEATING LOAD (MMBtu)	ENERGY SUPPLIED (MMBtu)		MEASURED SOLAR FRACTION (PERCENT)	AMBIENT TEMPERATURE (°F)
		SOLAR	AUXILIARY		
JUNE 1981	0	0	0	0	
JULY 1981	0	0	0	0	
AUGUST 1981	0	0	0	0	
SEPTEMBER 1981	0	0	0	0	
OCTOBER 1981	0	0	0	0	
NOVEMBER 1981	(a)	(a)	(a)	(a)	(a)
DECEMBER 1981	(a)	16.0	(a)	(a)	50
JANUARY 1981 ^(b)	28.0	12.5	15.5	45	52
FEBRUARY 1981	36.0	18.0	18.0	50	59
TOTAL	64.0	46.5	33.5	-	-
SEASON AVERAGE	32.0	15.5	16.8	48	54

(a) NOT AVAILABLE.

(b) THE VALUES ARE BASED ON A LINEAR EXTRAPOLATION FROM LAST 10 DAYS OF DATA IN JANUARY.

Table 2-5. Cooling Subsystem Performance

MONTH	COOLING LOAD (MMBtu)			SOLAR FRACTION		AUXILIARY ELECTRIC USED (MMBtu(e))			SOLAR ENERGY USED (MMBtu)	AMBIENT TEMPERATURE (°F)	DAYTIME AMBIENT TEMPERATURE (°F)
	TOTAL	FROM ^(a) EXISTING CHILLERS	FROM R/C-A/C CHILLERS	FRACTION OF TOTAL	FRACTION OF R/C-A/C	TOTAL	BY EXISTING CHILLERS	BY R/C CHILLERS			
JUNE 1981	704	474	230	0.065	0.251	215	166	48	184	93	99
JULY 1981	850	611	239	0.055	0.134	319	251	68	177	93	96
AUGUST 1981	774	563	211	0.052	0.131	284	219	65	174	93	97
SEPTEMBER 1981	626	386	240	0.060	0.156	228	160	68	135	87	94
OCTOBER 1981	329	138	191	0.056	0.156	110	59	51	107	72	82
NOVEMBER 1981	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
DECEMBER 1981	63	20	43	0.102	0.150	22	9	113	24	50	67
JANUARY 1982	38 ^(c)	0	38 ^(c)	0.230 ^(c)	0.230 ^(c)	10	0	10	31	52	58
FEBRUARY 1982	75 ^(c)	13 ^(c)	62 ^(c)	0.210 ^(c)	0.250 ^(c)	22	6	16	52	67	67
TOTAL	3459	2205	1254	0.071	0.145	1210	870	339	864	76	83
SEASON AVERAGE (JUNE-OCT)	657	434	223	0.066 ^(d)	0.145 ^(d)	231	171	60	155	88	94

(a) COOLING SUPPLIED BY THE WESTINGHOUSE CHILLERS

(b) NOT AVAILABLE.

(c) ESTIMATED USING PERFORMANCE DATA FOR PREVIOUS MONTH.

(d) AVERAGE VALUE OF MEASURED SOLAR FRACTION IS WEIGHTED BY LOAD.

In July and August 1981, the solar contribution of cooling load was lower than in June, even though the solar energy used for cooling was about the same. This was due to the poor performance of Rankine unit No. 1. The performance of unit No. 1 continually degraded from July through the end of August because of a Freon leak. This was repaired in the first week of September. In September and October the chiller units were only partly loaded most of the time due to the lower cooling load. As expected the performance of the chiller during those two months was lower than at full load. In the months of January and February 1982, cooling output could not be measured due to a bad temperature sensor in the chilled water loop. However, for those two months, the cooling outputs and solar cooling fractions were estimated using the measured auxiliary electric energy and solar energy values and performance data for October and December 1981. The season average values presented in the last row of Table 2-5 are monthly averages for the 5 months (June through October 1981) of the cooling season. An average of 6.6 percent of the building cooling demand was supplied by the solar system. The system or the Rankine chillers supplied 34 percent of the total building load; the remaining load was supplied by the existing Westinghouse chillers. Of the cooling supplied by the system or the Rankine chillers, the solar contribution was 19.5 percent. The solar contribution expressed as a percentage of the building cooling load was 6.6 percent.

2.2.5 Rankine Cycle Engine and Air Conditioner

In the cooling season solar energy is converted to shaft work by an organic Rankine-cycle engine. The shaft work is used to run a conventional vapor compression refrigeration-cycle air conditioner to provide cooling. Hot solar fluid is used to boil the Rankine-cycle working fluid (Freon 113), which is used to run a high-speed turbine. The high-speed turbine is connected to the low-speed (1750 rpm) motor through a single reduction gearbox. The gearbox is coupled to one end of the motor shaft through an over-running clutch, which allows the motor to run independently of the Rankine engine

when it is not operating, but which also allows the Rankine engine to assist the electric motor in driving its load. The opposite end of the motor shaft is coupled to the compressor for the air conditioner through an electric clutch. In this configuration, the motor may run the compressor by itself or with assistance from the Rankine-cycle engine. The Rankine-cycle engine also may be used to generate electricity by uncoupling the compressor from the electric motor (employing the electric clutch) and driving the motor as a generator. The power generation mode is used as a preferred alternative to rejecting excess collected energy to the environment (purging when there is no load).

At SRP two similar Rankine units were installed. The performance of these two units were measured in the laboratory before shipping and installation. At design conditions of 195°F solar inlet temperature and 85°F condenser water inlet temperature, unit No. 1 (Rankine engine and chiller) produced 22 tons of cooling. At these conditions the motor/generator drew 500 watts of electricity. The engine efficiency at these conditions was measured to be 7.6 percent. Unit No. 2, similarly constructed, produced 22 tons of cooling using solar energy at the same design conditions and drew 3300 watts of electricity to run the vapor compressor. Rankine engine No. 2 efficiency was measured to be 7.5 percent. The vapor compressor COP's for unit No. 1 and unit No. 2, defined as the cooling output to the shaft power input, were 5.2 and 4.6, respectively, at the design chilled water inlet temperature of 55°F.

The RC/AC performances for each month of operation for unit No. 1 and unit No. 2 are described below.

2.2.5.1 Unit No. 1--Over the 8-month test period (not including November) 406 MMBtu of collected solar energy was provided to the Rankine boiler No. 1. Table 2-6 summarizes the data for unit No. 1. About 97 percent of this was used for cooling and 3 percent was used for generation of electricity. Most of the energy generation occurred during times when Rankine unit No. 2

was not operational or during system maintenance when the unit was forced to generate. This happened because the chillers were nearly always loaded during the daytime and used all the shaft power produced by the engine. For any generation to occur the solar water inlet temperature must be over 200°F with the condenser water temperature at 85°F. The solar water inlet temperature seldom exceeded 200°F when both units were operating. For a performance measure, the vapor compressor (VC) COP is calculated as follows:

$$\text{COP(VC)} = \frac{\text{Cooling Produced}}{\left(\begin{array}{c} \text{Solar Energy} \\ \text{for Cooling} \end{array} \times \begin{array}{c} \text{Rankine} \\ \text{Efficiency} \end{array} \right) + \left(\begin{array}{c} \text{Auxiliary} \\ \text{Electric} \\ \text{Used} \end{array} \times \begin{array}{c} \text{Motor} \\ \text{Efficiency} \end{array} \right)}$$

Based on the overall data, the "annual" COP for unit No. 1 is calculated to be 4.1, using 0.85 for the motor efficiency and a nominal Rankine efficiency of 0.075. For the month of June 1981 the COP (VC) is calculated to be 5.0. This compares well with the laboratory data of 5.2. The COP(VC) decreased to 4.6 in July and to 4.1 in August. This was due to a Freon leak in the chiller, which was repaired in early September. The COP(VC) was 4.1 for September, 4.0 for October, and 3.5 for December, January and February. The lower COP in winter months was due to part loading of the chillers.

The Rankine engine efficiencies reported in Table 2-6 were estimated from a look-up table as a function of inlet solar fluid temperature and condenser water temperature. The look-up table was derived from test data obtained under laboratory conditions and represents the thermal efficiency that could be expected under ideal operating conditions. Analysis of power generation data (which gave the output of the Rankine engine directly from the power generated and the generator efficiency) indicated that at a 195°F solar water inlet temperature and a condenser water inlet temperature of about 85°F, the engine generated about 12 kW of power or about 20 hp at the Rankine shaft (assuming 0.8 generator efficiency). This compares well with

Table 2-6. Rankine Cycle Summary: Unit No. 1

MONTH	SOLAR ENERGY USED (MMBtu)		RANKINE ENGINE EFFICIENCY (PERCENT) (ESTIMATE)	AUXILIARY ELECTRIC USED (MMBtu)	OPERATING ELECTRIC ENERGY USED (MMBtu)		GENERATED ELECTRIC ENERGY (MMBtu)	COOLING PRODUCED	
	FOR COOLING	FOR GENERATION			FOR COOLING	FOR GENERATION		TOTAL (MMBtu)	SOLAR FRACTION
JUNE 1981	77	2	7.5	21.8	7.4	0.05	0.15	120	0.258
JULY 1981	78	4	7.5	32.5	9.7	0.12	0.22	139	0.194
AUGUST 1981	61	0	7.5	30.4	8.5	0	0	125	0.150
SEPTEMBER 1981	61	3	7.5	32.8	9.0	0.12	0.16	132	0.141
OCTOBER 1981	52	0	7.5	26.8	7.7	0	0	106	0.146
NOVEMBER 1981	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
DECEMBER 1981	24	1	7.5	12.5	4.2	0.03	0.06	43	0.145
JANUARY 1982	20	1	7.5	7.1	2.5	0.03	0.06	27 ^(b)	0.200
FEBRUARY 1982	19	3	7.5	3.8	1.7	0.10	0.15	17 ^(b)	0.306
TOTAL	392	14	7.5	167.7	50.7	0.46	0.80	709	0.171

(a) NOT AVAILABLE.

(b) ESTIMATED USING PERFORMANCE DATA FOR DECEMBER AND OCTOBER.

the laboratory data which under these same conditions indicated a 20-hp output at the Rankine shaft.

2.2.5.2 Unit No. 2: Rankine unit No. 2 used 492 MMBtu of collected solar energy for cooling and 21 MMBtu for generation during the 8-month test period. Table 2-7 summarizes the data for this unit.

The annual vapor compressor COP is calculated is to be 3.0 using a nominal Rankine efficiency of 7.5 percent. The COP(VC) for June was 3.5; it decreased in July and August steadily to 2.7 and 2.3, respectively. This decrease was apparently due to a slow leak of refrigerant from the system, which was fixed during the first week of September. The chiller COP in September thus increased to 3.1 and in October was 3.4. Laboratory measurement data indicated an expected COP(VC) of 4.6. Analysis of the chiller data when there was no solar energy available and measurements made manually at site showed 18.3 tons of cooling at full load and a vapor compressor COP of 3.8. No known cause was determined for the performance of this unit below laboratory measurement.

Under design conditions (195°F solar inlet temperature to the Rankine boiler and 85°F condenser inlet temperature), the unit was expected to generate 11.3 kW or 18.9 hp at the Rankine shaft. However, analysis of power generation data from June through October showed that the engine generated 10 kW or 16.8 hp at the Rankine shaft. Near the end of the test period, data showed that the engine was generating only 8.8 kW or 14.8 hp at the Rankine shaft. The precise cause of the degrading engine performance was never determined during the operational test period. However, possible causes could be a flow restriction on the Rankine working fluid or air entrapment (Rankine working fluid R-113 is normally subatmospheric) in the condenser.

Table 2-7. Rankine Cycle Summary: Unit No.2

MONTH	SOLAR ENERGY USED (MMBtu)		RANKINE ENGINE EFFICIENCY (PERCENT) (ESTIMATE)	AUXILIARY ELECTRIC USED (MMBtu)	OPERATING ELECTRIC ENERGY USED (MMBtu)		GENERATED ELECTRIC ENERGY (MMBtu)	COOLING PRODUCED	
	FOR COOLING	FOR GENERATION			FOR COOLING	FOR GENERATION		TOTAL (MMBtu)	SOLAR FRACTION
JUNE 1981	107	1	7.1	26.1	8.1	0.03	0.03	107	0.266
JULY 1981	99	3	7.5	35.0	10.3	0.12	0.18	100	0.200
AUGUST 1981	113	0	7.5	34.6	11.1	0	0	86	0.224
SEPTEMBER 1981	74	4	7.5	35.1	9.6	0.13	0.27	108	0.157
OCTOBER 1981	55	9	7.5	24.6	6.6	0.32	0.54	85	0.165
NOVEMBER 1981	(a)	(a)	-	(a)	(a)	(a)	(a)	(a)	(a)
DECEMBER 1981	0	0	7.5	0	0	0	0	0	0
JANUARY 1982	11	1	7.5	2.8	0.8	0.03	0.08	11(b)	0.237
FEBRUARY 1982	33	3	7.5	12.0	4.1	0.13	0.18	45(b)	0.195
TOTAL	492	21	7.5	170.2	50.6	0.73	1.28	542	0.203

(a) NOT AVAILABLE.

(b) ESTIMATED USING PERFORMANCE DATA FOR DECEMBER AND OCTOBER.

SECTION 3.0
OPERATING ENERGY

Operating energy is defined as the electrical energy used by the system, to perform its functions, which does not directly influence the thermal state of the system. This consists of the energy used to power the pumps and fans within the system. The energy used by the system controls and the flow control valves was not instrumented since the power usage of these parts is very low.

Table 3-1 lists the monthly operating energy consumed by the complete HVAC system and its subsystems. This is further broken down to present the operating energy used by the conventional equipment and the solar energy system. The Energy Collection and Storage Subsystem (ECSS) operating energy is the energy used by the purge unit only. The energy used by collector loop pumps is assigned to the active subsystem. The space cooling operating energy consists of all energy used to support the cooling subsystem, including the cooling towers and condenser pumps. Solar-specific cooling operating energy includes solar pumps, Rankine condenser pumps, Rankine parasitics and a portion of the cooling tower energy consumption.

Table 3-1. System Operating Energy

MONTH	ECSS ^(a) OPERATING ENERGY [MMBtu(e)]	SPACE COOLING OPERATING ENERGY [MMBtu(e)]					SPACE HEATING OPERATING ENERGY [MMBtu(e)]			ENERGY GENERATION OPERATING ENERGY [MMBtu(e)]	TOTAL OPERATING ENERGY [MMBtu(e)]		
		TOTAL	EXISTING CHILLERS	R/C-A/C CHILLERS AUXILIARY MODE	R/C-A/C CHILLERS SOLAR- ASSIST MODE	SOLAR SPECIFIC	TOTAL	AUXILIARY MODE	SOLAR SPECIFIC		TOTAL ^(b) SYSTEM	SOLAR R/C-A/C SYSTEM ^(c)	SOLAR SPECIFIC
JUNE 1981	0.9	76.1	60.6	6.5	9.0	5.6	0	0	0	0.09	77.0	16.5	5.7
JULY 1981	0.4	99.9	79.9	10.4	9.6	6.0	0	0	0	0.24	100.3	20.4	6.2
AUGUST 1981	1.0	99.2	79.6	10.5	9.1	5.8	0	0	0	0	100.2	20.6	5.8
SEPTEMBER 1981	0.6	87.1	68.5	11.0	7.6	4.9	0	0	0	0.25	87.9	19.4	5.1
OCTOBER 1981	0.4	55.0	40.7	8.3	6.0	3.8	0	0	0	0.32	55.8	15.1	4.1
NOVEMBER 1981	(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)
DECEMBER 1981	0.2	24.5	20.3	2.7	1.5	1.0	1.2	0	1.2	0.03	26.0	5.7	2.2
JANUARY 1982	0.0	21.5	18.2	1.8	1.5	0.9	0.9	0	0.9	0.06	22.5	4.3	1.9
FEBRUARY 1982	0.2	24.2	18.3	2.9	3.0	1.8	1.0	0	1.0	0.21	25.6	7.3	3.0
TOTAL	3.7	487.5	386.1	54.1	47.3	29.8	3.1	0	3.1	1.20	495.3	109.3	34.0
AVERAGE	0.5	60.9	48.3	6.8	5.9	3.7	0.4	0	0.4	0.15	61.9	13.7	4.3

(a) PURGE UNIT ONLY.

(b) INCLUDES BUILDING CHILLER.

(c) DOES NOT INCLUDE BUILDING CHILLER.

(d) NOT AVAILABLE.

SECTION 4.0
ENERGY SAVINGS

Whenever solar energy is used instead of, or in addition to, auxiliary energy, energy savings can be realized. The energy saved by the SRP solar heating and cooling system was determined by a comparison of the energy used by the system with the energy that would have been required by assumed conventional HVAC subsystems. The assumed conventional subsystems were the system's auxiliary load subsystems (radiant heaters and a motor-driven air conditioner). Energy used by components common to the solar and conventional subsystems (such as the chiller pump and the air conditioner condenser) was ignored because of their commonality. The energy used to support solar energy collection, storage and delivery was necessarily debited against the energy savings, and the power generated was credited to the energy savings. All energy savings are electric because all auxiliary subsystems are electrical.

The electrical energy savings of the SRP solar system for the period between June 1981 and February 1982 (excluding November 1981) are listed by subsystem in Table 4-1. The table lists the gross electrical energy savings, the operating energies, and the resultant net energy savings. Over the period reported in the table, the net electrical savings were 26,200 kWh(e). The monthly savings are highest in the heating season, when solar energy replaced electrical resistance heating. Assuming average monthly heating season savings for November and average monthly cooling season savings for March, April and May, the net annual electrical savings due to the solar system are expected to be 39,000 kWh(e).

Table 4-1. Energy Savings

MONTH	GROSS ELECTRICAL ENERGY SAVINGS [MMBtu(e)]				OPERATING ENERGY [MMBtu(e)]					NET ELECTRIC ENERGY SAVINGS	
	TOTAL	SOLAR HEATING	SOLAR COOLING	ENERGY GENERATION	TOTAL	SOLAR HEATING	SOLAR COOLING	ENERGY GENERATION	ECSS	[MMBtu(e)]	kWh(e)
JUNE 1981	16.4	0	16.2	0.18	6.6	0	5.6	0.09	0.9	9.8	2,872
JULY 1981	16.0	0	15.6	0.40	6.6	0	6.0	0.24	0.4	9.4	2,755
AUGUST 1981	15.4	0	15.4	0	6.8	0	5.8	0	1.0	8.6	2,520
SEPTEMBER 1981	12.3	0	11.9	0.43	5.7	0	4.9	0.25	0.6	6.6	1,934
OCTOBER 1981	10.5	0.5	9.5	0.54	4.5	0	3.8	0.32	0.4	6.0	1,758
NOVEMBER 1981	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
DECEMBER 1981	18.2	16.0	2.1	0.06	2.4	1.2	1.0	0.03	0.2	15.8	4,630
JANUARY 1981	15.3	12.5	2.7	0.14	1.9	0.9	0.90	0.06	0.0	13.4	3,927
FEBRUARY 1981	23.0	18.0	4.6	0.34	3.2	1.0	1.8	0.21	0.2	19.8	5,804
TOTAL	127.1	47.0	78.0	2.09	37.7	3.1	29.8	2.20	3.7	89.4	26,200
AVERAGE	15.9	5.9	9.8	0.30	4.7	0.4	3.7	0.15	0.5	11.2	3,275

(a) NOT AVAILABLE.

4.1 ALTERNATE METHOD OF ENERGY SAVING CALCULATION

The vapor compressors (Rankine chillers) installed as part of the solar system had a better coefficient of performance than the existing Westinghouse chillers. Operating these Rankine chillers for cooling during times when solar energy was not available resulted in an additional energy savings to the OTS. Therefore, the energy savings realized were significantly higher than that reported above. The cooling electrical energy savings due to the operation of the Rankine chillers in both the solar-assisted and auxiliary mode are calculated using the measured performance data as follows:

1. Total cooling produced by Westinghouse during OTP	=	2205 MMBtu
2. Total auxiliary electrical energy consumed including operating energy	=	1110 MMBtu
3. COP (Westinghouse chillers)	=	2.0
4. Total cooling produced by Rankine chillers	=	1254 MMBtu
5. Total electrical energy consumed including operating energy for the solar system	=	448 MMBtu
6. COP (solar-Rankine system)	=	2.8
7. Electrical consumption if cooling in Step 4 was provided by Westinghouse chillers (1254/2.0)	=	627 MMBtu
8. Net cooling electrical energy saved (Step 7 - Step 5)	=	179 MMBtu
or 52460 kWh(e)
9. Net electrical energy saved due to other solar subsystems (Heating, generation)	=	41 MMBtu
or 12040 kWh(e)
10. Total electrical energy saved during the OTP (8-month period) (Step 8 + Step 9)	=	64500 kWh(e)

11. Total annual electrical energy
 saved (estimate) = 97000 kWh(e)

Therefore, the net annual electrical energy savings realized by the Operational Test Site was 97,000 kWh(e).

SECTION 5.0

MAINTENANCE

Most of the components in the solar energy system performed well. A summary of the system maintenance log is shown in Table 5-1. The Rankine-cycle air conditioner, being a prototype machine, experienced some unintentional shutdowns. Unit No. 1 occasionally did not start due to low lubrication pressure. Most of the system maintenance on this unit was performed to rectify this problem. These efforts have not been completely successful and, at the end of the test period, the unit was still experiencing this problem.

Since the Rankine condensers operate at subatmospheric pressures, there is a possibility of air leaking into the system. An automatic air purge system is provided with each unit to discharge this air. Occasional problems with these automatic systems were experienced. Therefore, the system was periodically purged manually.

The heating units, located about 200 feet from the thermal storage tank, initially blew cold air for a few minutes. This was because a warm-up period was needed to provide the heat loss in the piping. To rectify this, a 5-minute time delay relay was installed on the fan motors. In addition, when the supply temperature dropped below 140°F, the air temperature from the unit heaters was at an uncomfortable level. Thus, the minimum temperature set points for discharging from storage to heating and for charging storage were raised to 140°F.

Table 5-1. System Maintenance Log

SUBSYSTEM	PROBLEMS	ACTION	DATE OF ACTION
COLLECTOR	BROKEN GLASS ON ONE PANEL; CAUSE UNKNOWN	REPLACED	MAY 1981
SOLAR CONTROL PANEL	INTERMITTENT PROBLEM WITH CIRCULATING PUMP OPERATION	INSTALLED 150V VARISTOR ACROSS INDUCTIVE WIRES IN PANEL	JUNE 1981
	UNSTABLE TEMPERATURE READOUT; ERRATIC SYSTEM OPERATION	MODIFIED PUMP OPERATION LOGIC AND ALARM MODES AND REPLACED PROM'S	JULY 1981
RANKINE UNIT 1	ENGINE FAILS TO START: INTER- MITTENT PROBLEM; DIRTY LUBE SYSTEM ENGINE START-UP PROBLEM LEAK AT MAGNETIC PLUG IN OIL LINE ENGINE START-UP PROBLEM	REPLACED HIGH-PRESSURE BURST DISK	JUNE 1981
		TIGHTEN SET SCREWS ON MOTOR TO GEARBOX COUPLING	JUNE 1981
		CLEANED LUBE JETS OF GEARBOX, REPLACED IN-LINE FILTER AND PURGED AIR FROM SYSTEM	JULY 1981
		ADDED REFRIGERANT (40 LBS OF R-113)	AUGUST 1981
		REPLACED IN-LINE OIL STRAINER AND SOLENOID VALVE ON OIL LINE TO GEARBOX	AUGUST 1981
		PRESSURIZED SYSTEM AND CHECKED FOR LEAKS; PURGED SYSTEM	SEPTEMBER 1981
RANKINE UNIT 2	REFRIGERANT LEAK FROM CHILLER UNIT 2 CHECK VALVE ON CONDENSER; PUMP LINE STICKS LEAK AT COMPRESSOR DISCHARGE VALVE	FIXED LEAK AND ADDED REFRIGERANT	SEPTEMBER 1981
		PURGED AIR FROM RANKINE CONDENSER	SEPTEMBER 1981
		REPAIRED WIRE CONNECTIONS OF SOLENOID STOP VALVE	SEPTEMBER 1981
		REPLACED BEARINGS ON UNIT 2 MOTOR	JANUARY 1982
		CLEANED CHECK VALVE	FEBRUARY 1982
		REPAIRED AND CHARGED SYSTEM WITH R-12	FEBRUARY 1982
STORAGE AND HEATING	BLOWS COLD AIR WHEN STORAGE TEMPERATURE BELOW 140°F	CHANGED TEMPERATURE SET POINTS ON SOLAR FLUID FOR STORAGE CHARGING AND SET POINT ON DIS- CHARGING TO 140°F. INSTAL- LED TIME DELAY RELAY FOR FAN MOTOR.	FEBRUARY 1982

SECTION 6.0
SUMMARY AND CONCLUSIONS

This report provides a summary of the performance of the solar heating and cooling system at the Salt River Project, Phoenix, Arizona, over the operational test period from April 1981 to March 1982. This analysis was conducted by evaluation of measured system performance and by comparison of measured climatic data with long-term average climatic conditions for the site. The following observations were made:

1. Measured average daily insolation for the year was about 18 percent lower and the measured average daily ambient temperature for the year was about 4 F⁰ warmer than the long-term average, both in the heating and cooling seasons. The result was a higher building cooling load and a smaller solar contribution to the cooling load than expected (simulation) in a typical meteorological year (TMY).

Extrapolating the measured values over the entire year, the solar system provided 386 MMBtu of cooling and 61 MMBtu of heating. Similarly, the extrapolated net annual electrical savings was 39,000 kWh(e), based on a savings of 26,200 kWh(e) during the operational test period, which was less than 12 months long. Note that net annual electrical savings in a TMY is expected to be 25 percent more than the 39,000 kWh(e) value. (See Section 4.0 for an alternate discussion of energy savings.)

2. The relative sizes of the solar cooling system and conventional cooling system must be considered when discussing solar contribution. The 50 tons (two 25-ton solar Rankine-cycle air conditioning machines at design condition) of solar cooling potential supplements the existing 250-ton conventional chiller. Therefore, a relatively low overall contribution is inherent in the application. Note that 7.1 percent of the total building cooling load and 48 percent of the heating load were provided by solar energy.

The intentional undersizing results in a very large load for the solar cooling system; the load typically consumes the total Rankine-cycle air conditioner cooling output during most days of the year. The overall solar energy utilization (or solar system efficiency) is therefore maximized, as solar energy is used to drive the compressor directly via the Rankine-cycle turbine, rather than to store the energy for later use (in the thermal storage tank or "stored" as generated electricity in the grid).

3. The purge unit, designed to reject excess solar thermal energy, operated about 200 of the total 1500 hours of system operation. Since the system is designed for purge operation to occur only when one or both Rankine-cycle air conditioner units is "down," the purging indicates unused solar energy. The effect is an estimated 10 percent reduction in net energy savings during the OTP.
4. The microprocessor-based system control panel--with its enhanced logic, monitoring and diagnostic capabilities--as compared to controllers at other 404 sites, increased the effectiveness of the system. Though the overall effect is not quantified readily, it can be qualified by such issues as:
 - Reduced start-up/shutdown cycling.
 - Improved utilization (staging and selection) of the dual 25-ton Rankine-cycle air conditioning units.
 - Enhanced system controls troubleshooting.
5. There exists, for this and most probably for other solar Rankine-cycle air conditioning systems, definable insolation and temperature thresholds for system operation. Specific examples are the turn-on and turn-off of system pumps and the Rankine-cycle air conditioning

units; the difference is related to the system's thermal dynamics. The SRP system controls were "tuned" with the thresholds (see Table 6-1) such that the system pump cycles only twice before continuous operation during start-up (about 5 minutes), and it typically turns off when the last Rankine-cycle air conditioner turns off in the afternoon.

6. A limited performance calculation error analysis was conducted (see Appendix D).

Table 6-1. Thresholds for Various Events

EVENT	INCIDENT* INSOLATION (Btu/FT ² -HR)	COLLECTOR OUTLET TEMPERATURE (°F)
SYSTEM TURN-ON INITIAL CONTINUOUS OPERATION	140-150 165-180	NA 140
RC TURN-ON FIRST UNIT SECOND UNIT	175-195 200-205	160 170
RC TURN-OFF FIRST UNIT LAST UNIT	175-175 100-100	150 160
SYSTEM TURN-OFF	100-100	150
PURGE UNIT ON BOTH RC/AC OPERATIONAL ONE RC/AC DOWN BOTH RC/AC DOWN	350** 270 175**	>220 >220 >220
PEAK MEASURED INSOLATION	310-290	200-190

* Range from mid to late summer days

** Estimate

SECTION 7.0

REFERENCES

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APPENDIX A
DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

A.1 COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected:

- Incident Solar Energy (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework, which is an integral part of the collector structure.
- Operational Incident Energy (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).
- Collected Solar Energy (SECA) is the thermal energy removed from the collector array by the energy transport medium.
- Collector Array Efficiency (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures that are determined from instantaneous test data obtained during steady-state operation of a single collector unit. These efficiency figures often are provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum

efficiency factor will be significantly higher than the collector array efficiency reported herein.

- Daytime Ambient Temperature (TDA) is the temperature during the period from 3 hours before solar noon to 3 hours after solar noon.

A.2 STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy:

- Energy to Storage (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.
- Energy from Storage (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.
- Change in Stored Energy (STECH) is the difference in the estimated stored energy during the specified reporting period as indicated by the relative temperature of the storage medium (either positive or negative value).
- Storage Average Temperature (TST) is the mass-weighted average temperature of the primary storage medium.
- Storage Efficiency (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

A.3 ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, and the transport loops between these and other components in the system design which are necessary to mechanize the collector and storage equipment.

- Incident Solar Energy (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework, that is an integral part of the collector structure.
- Ambient Temperature (TA) is the average temperature of the outdoor environment at the site.
- Energy to Loads (SEL) is the total thermal energy transported from the ECSS to all load subsystems.
- ECSS Operating Energy (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.
- ECSS Rejected Energy (CSRJE) is the energy intentionally rejected by the purge unit to protect against overtemperature and to prevent damage to the system components.
- ECSS Solar Conversion Efficiency (CSCEF) is the ratio of the solar energy delivered to the load subsystems to the incident solar energy.

A.4 SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average

building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space-heating load and in controlling the temperature of the conditioned space.

- Space Heating Load (HL) is the sensible energy added to the air in the building.
- Solar Fraction of Load (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.
- Solar Energy Used (HSE) is the amount of solar energy supplied to the space-heating subsystem.
- Operating Energy (HOPE) is the amount of electrical energy that is required to support the subsystem (e.g., fans, pumps, etc.) and that is not intended to affect the thermal state of the subsystem directly.
- Electrical Energy Savings (HSVE) is the cost of the operating energy (HOPE) required to support the solar energy portion of the space-heating subsystem.
- Building Temperature (TB) is the average heat-space dry-bulb temperature on the days when there is a load to be satisfied.
- Ambient Temperature (TA) is the average ambient dry-bulb temperature at the site.

A.5 ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data that is generally instrumented at each site in the development program. It is

tabulated in this report for two purposes: (1) as a measure of the conditions prevalent during the operation of the system at the site, and (2) as a historical record of weather data for the vicinity of the site.

- Total Insolation (SE) is the accumulated total solar energy incident upon the gross collector array measured at the site.
- Ambient Temperature (TA) is the average temperature of the environment at the site.
- Daytime Ambient Temperature (TDA) is the temperature during the period from 3 hours before solar noon to 3 hours after solar noon.

A.6 SPACE-COOLING SUBSYSTEM

The space-cooling subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space-cooling load and in controlling the temperature of the conditioned space.

- Space-Cooling Load (CL) is the amount of thermal energy removed from the air-conditioned space of the building by all central SCS solar- and auxiliary-powered equipment.
- Solar Fraction of Load (CSFR) is the percentage of the SCS load demand that is supplied from the chillers when driven by the solar- powered Rankine-cycle turbines.

- Solar Energy Used (CSE) is the amount of solar energy supplied from the ECSS to the space-cooling subsystem which is used to satisfy the space-cooling load.
- Operating Energy (COPE) is the amount of electrical energy required to support the operation of the space-cooling subsystem (e.g., fans, pumps, etc.) that is not intended to affect the thermal state of the subsystem directly.
- Auxiliary Thermal Used (CAT) is the equivalent thermal energy supplied to the space-cooling subsystem by the subsystem auxiliary equipment.
- Auxiliary Electrical Fuel (CAE) is the amount of electrical energy supplied to the space-cooling subsystem auxiliary electrical equipment.
- Electrical Energy Savings (CSVE) is the estimated difference between the electrical energy requirements of a conventional space-cooling system (carrying the full cooling load) and the electrical energy required by the actual solar-assisted subsystem.
- Building Temperature (TB) is the average heat-space dry-bulb temperature on the days when there is a load to be satisfied.
- Ambient Temperature (TA) is the average ambient dry-bulb temperature at the site.

A.7 RANKINE CYCLE SUMMARY

The Rankine cycle summary is a combination of performance factors that outline the performance of the Rankine-cycle air conditioners during space-cooling and power-generation operation.

- Solar Energy Used (RSE) is the amount of solar energy supplied from the ECSS to the Rankine-cycle air conditioners that is used to satisfy the space-cooling load and generate electricity.
- Turbine Output (RANKOUT) is the predicted shaft output of the Rankine-cycle turbine based on the solar water temperature and flow rate and the cooling tower sump water temperature.
- Rankine Thermal Efficiency (REFF) is the predicted thermal efficiency of the Rankine-cycle turbine based on the solar water temperature and flow rate and the cooling tower sump water temperature.
- Auxiliary Electricity Used (CAE) is the amount of electrical energy supplied to the space-cooling subsystem auxiliary electrical equipment.
- Parasitic Power (PARASITICS) is the electrical energy used to satisfy the power needs of the Rankine-cycle air conditioner internal components (e.g., booster and feed pumps, controls, heaters, etc.)
- Operating Energy (TCEOPE) is the amount of electrical energy required to support the operation of the Rankine-cycle air conditioners (e.g., pumps, fans, etc.) that is not intended to affect the thermal state of the subsystem directly.
- Energy Rejected (TCERJE) is the thermal energy rejected from the Rankine-cycle turbine condensers and chiller condensers by the cooling tower.
- Power Generated (PWRGEN) is the electrical power produced by the auxiliary motor when being driven as a generator by the Rankine-cycle turbine.

- Cooling Produced (OUTVC) is the amount of thermal energy removed from the air-conditioned space of the building by all central SCS solar- and auxiliary-powered equipment.
- Coefficient of Performance (TCECOP) is the ratio of the cooling load plus the power generated normalized to cooling output to solar energy used by the Rankine cycle turbine plus the auxiliary electricity used normalized to solar energy input to the Rankine-cycle turbine.
- Solar Water Temperature (TRANKS) is the mass flow rate averaged temperature of the solar water during Rankine-cycle turbine operation.
- Condensing Water Temperature (TRANKC) is the mass flow rate averaged temperature of the cooling tower sump water during Rankine-cycle turbine operation.
- Rankine-Engine-Assisted is a term used to describe the solar-powered air conditioner machine. Specifically, "Rankine" refers to this solar engine's thermodynamic cycle; "assisted" infers that the engine does not provide all power to drive the chiller, but unloads the 20 hp motor/generator.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR
SALT RIVER PROJECT, PHOENIX, ARIZONA (OTS 45)

B.1 INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data then is combined numerically to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are integrated numerically to provide discrete approximations of the continuous functions that characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations that are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{Solar Energy Available} = (1/60) \int [I001 \times \text{CLAREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft²-hr, CLAREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{Collected Solar Energy} = \int [M100 \times \Delta H] \times \Delta \tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m , of the fluid as it passes through the heat exchanging component.

For a liquid system

$$\Delta H = C_p \Delta T$$

where C_p is the average specific heat (in $\text{Btu}/\text{lb}_m\text{-}^\circ\text{F}$) of the heat transfer fluid and ΔT (in $^\circ\text{F}$) is the temperature differential across the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS Operating Energy} = (3413/60) \int [EP100] \times \Delta \tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/minute .

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of 1 hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy

parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

B.2 PERFORMANCE EQUATIONS

The performance equations for the Salt River Project (SRP) used for the data evaluation of this report are contained in the following pages and have been included for technical reference and information.

B.2.1 Equations Used in Monthly Performance Assessment

Measurement numbers reference the system schematic in Figure B-1.

- Enthalpy Function for Water (Btu/lbm)

$$\text{HWD } (T_2, T_1) = \int_{T_1}^{T_2} C_p(T) dT$$

This function computes the enthalpy change of water as it passes through a heat exchanging device.

- Average Ambient Temperature ($^{\circ}\text{F}$)

$$TA = (1/60) \times \sum T_{001} \times \Delta\tau$$

- Daytime Average Ambient Temperature ($^{\circ}\text{F}$)

$$\text{TDA} = (1/360) \times \sum \text{T001} \times \Delta\tau$$

for ± 3 hours from solar noon.

- Incident Solar Energy per Square Foot (Btu/ft^2)

$$\text{SE} = (1/60) \times \sum \text{I001} \times \Delta\tau$$

- Incident Solar Energy (Btu)

$$\text{SEA} = (1/60) \times \sum [\text{I001} \times \text{CLAREA}] \times \Delta\tau$$

- Operational Incident Solar Energy (Btu)

$$\text{SEOP} = (1/60) \times \sum [\text{I001} \times \text{CLAREA}] \times \Delta\tau$$

when the collector loop is active (EP100 or $\text{EP101} > 0$).

- Solar Energy Collected by the Array (Btu)

$$\text{SECA} = \sum [\text{M100} \times \text{C}_p \times (\text{T150} - \text{T100})] \times \Delta\tau$$

- Solar Energy to Storage (Btu)

$$\text{STEI} = \text{M100} \times \text{C}_p \times (\text{T151} - \text{T250})$$

when flow to Rankine units is zero.

- Energy Removed from Storage to Heating Loop (Btu)

$$\text{STEI} = \text{M400} \times \text{C}_p \times (\text{T201} - \text{T450})$$

- Average Temperature of Storage ($^{\circ}\text{F}$)

$$\text{TST} = (1/60) \times \sum [(T202 + T203 + T204)/3] \times \Delta\tau$$

- Energy Rejected by Purge Unit (Btu)

$$\text{CSRJE} = \sum M100 \times \text{HWD} (T151, T150) \times \Delta\tau$$

- Solar Energy to Heating (Btu)

$$\text{HSE} = \sum M400 \times C_p \times (T201 - T450)$$

- System Cooling Load (Btu)

$$\text{CL} = \sum M600 \times \text{HWD} (T651, T650) \times \Delta\tau$$

- Rankine Chiller Cooling (Btu)

$$\text{OUTVC} = \sum M502 \times \text{HWD} (T502, T553) \times \Delta\tau$$

- Solar Energy to Rankine (Btu)

$$\text{RSE1} = \sum M560 \times C_p \times (T560 - T562) \times \Delta\tau$$

$$\text{RSE2} = \sum M561 \times C_p \times (T562 - T563) \times \Delta\tau$$

- Space-Cooling Building Chiller Electrical Energy (Btu)

$$\text{CAE} = \sum (\text{EP600} + \text{EP601}) \times \Delta\tau \times \text{EPCONST}$$

- Space-Cooling Rankine Chiller Electrical Energy (Btu)

$$\text{RSCAE} = \sum [(\text{EP511} - \text{TP521}) + (\text{EP512} - \text{EP522})] \times \Delta\tau \times \text{EPCONST}$$

- Space-Cooling Total Auxiliary Electrical Energy

$$TCAE = CAE + RSCAE$$

- Total System Operating Energy (Btu)

$$\begin{aligned} SYSCOPE = EPCONST \times \sum [EP100 + EP101 + EP102 + EP400 + EP502 \\ + EP510 + EP513 + EP521 + EP522 + EP571 + EP572 + EP581 \\ + EP582 + EP800] \times \Delta\tau \end{aligned}$$

- ECSS Operating Energy (Btu)

$$CSOPE = EPCONST \times [EP102] \times \Delta\tau$$

- RANKINE Subsystem Operating Energy (Btu)

$$\begin{aligned} TCEOPE = EPCONST \times \sum [EP100 + EP101 + EP502 + EP510 + EP513 \\ + EP521 + EP522 + EP571 + EP572 + EP581 + EP582] \times \Delta\tau \end{aligned}$$

Not all of the pump and fan powers are used in each operating mode. The Rankine subsystem operating energy is further divided into operating energy by mode in the software.

- Rankine Turbine Thermal Efficiency (%)

$$REFF = \sum [RCHEFF (25, W561, T560, T510/60)] \times \Delta\tau$$

Where RCHEFF refers to a look-up table of predicted thermal efficiency based on the solar fluid temperature and sump water temperature.

- Rankine Shaft Output (Btu)

$$RANKOUT = \sum [RSE \times REFF \times 60] \times \Delta\tau$$

- Solar Energy Used for Space Cooling (Btu)

$$CSE = \sum [RSE \times (RANKOUT - PWROUT)/RANKOUT] \times \Delta\tau$$

- Power Generated (Btu)

$$PWROUT = \sum (EP507 + EP508 + EP521 + EP522) \times EPCONST \times \Delta\tau$$

when EP507 and/or EP508 are positive.

- Collector Array Efficiency

$$CAREF = SECA/SEA$$

- Storage Energy Change (Btu)

$$STECH = [STOCAP \times RHO(TST) \times C_p(TST)]_1 - [STOCAP \times RHO(TST) \times C_p(TST)]_2$$

where STOCAP is the volume of water in the storage tank.

- Space Heating Load (Btu)

$$HL = HSE + HAT$$

- Heating Auxiliary Thermal (Btu)

$$HAT = \sum (EP401 + EP402 + EP403) \times \Delta\tau \times EPCONST$$

- Heating Solar Fraction

$$HSFR = HSE/(HSE + HAT)$$

- Heating Subsystem Operation Energy (Btu)

$$\text{HOPE} = \text{EPCONST} \times \sum (\text{EP100} + \text{EP101} + \text{EP400}) \times \Delta\tau$$

EP400 is used during heating from storage.

EP100 and EP101 are used in storage charging mode only.

- Space Heating Electrical Energy Savings (Btu)

$$\text{HSVE} = \text{HSE} - \text{HOPE}$$

- Rankine Cooling Solar Fraction

$$\text{RCSFR} = \text{RANKOUT} / (\text{RANKOUT} + \text{RSCAE} \times 0.85)$$

0.85 is the motor efficiency.

- Cooling Solar Fraction

$$\text{CSFR} = \text{RCSFR} \times \text{OUTVC} / \text{CL}$$

- Chiller COP

$$\text{COPVC} = \text{OUTVC} / (\text{CAE} \times 0.85 + \text{RANKOUT})$$

- Space-Cooling Electrical Energy Savings (Btu)

$$\text{CSVE} = \text{OUTVC} / \text{COPVC} - \text{RSCAE} - \text{COPE}$$

- Space-Cooling Subsystem Operating Energy (Btu)

$$\text{COPE} = \text{EPCONST} \times \sum (\text{EP100} + \text{EP502} + \text{EP510} + \text{EP511} + \text{EP512} + \text{EP513} + \text{EP571} + \text{EP572} + \text{EP581} + \text{EP582}) \times \Delta\tau$$

Not all of the pump and fan powers are used in each operating mode. The cooling subsystem operating energy is calculated by mode in the software.

APPENDIX C

SITE DATA ACQUISITION AND PROCESSING
SALT RIVER PROJECT, PHOENIX, ARIZONA

The Salt River Project Site Data Acquisition Subsystem (SDAS) consists of 66 sensors, an electrical junction box and an SDAS module. The descriptions and designations of all sensors are listed in Table C-1 and their locations are shown in Figure C-1. The module samples the sensor readings and stores the data on magnetic tape. Temperature and electrical power are sampled at 32-second intervals and 10 measurements are averaged to generate the values which are stored on tape at 320-second intervals. Flow rates are sampled and stored only once during each period, at the end of the 320-second interval; this results in an instantaneous flow rate representing the flow for the whole period. The SDAS module transfers the stored data via telephone at the end of each day to a Central Data Processing System operated by Automation Industries Inc., Vitro Laboratories Division. The data then are stored on magnetic disc and/or magnetic tape.

At the end of each month, the data are reduced by the central computer using a program (called the site performance equations or Site Equation Document) that is unique to the site. Hourly, daily and monthly values for each performance parameter are calculated and printed. These reduced data were used to write this report. All raw data are archived at Vitro Laboratories Division for future reference.

Table C-1. SDAS Sensor Description (OTS 45)

SENSOR	DESCRIPTION	SENSOR	DESCRIPTION
T001	AMBIENT TEMPERATURE	T572	COOLING WATER TEMPERATURE AT RANKINE 2 CONDENSER OUTLET
T100	COLLECTOR FLUID INLET TEMPERATURE	T581	COOLING WATER TEMPERATURE AT CHILLER 1 CONDENSER OUTLET
T150	COLLECTOR FLUID OUTLET TEMPERATURE	T582	COOLING WATER TEMPERATURE AT CHILLER 2 CONDENSER OUTLET
T151	PURGE OUTLET TEMPERATURE	T502	CHILLER FLUID TEMPERATURE AT CHILLER 2 INLET (OR) CHILLER FLUID RETURN TEMPERATURE
T201	STORAGE FLUID TEMPERATURE--TOP OF TANK	T600	CHILLED WATER SUPPLY TEMPERATURE AT INLET TO EXISTING 228T CHILLER
T202	STORAGE FLUID TEMPERATURE--MIDDLE OF TANK	T650	CHILLED WATER SUPPLY TEMPERATURE AT OUTLET FROM EXISTING 228T CHILLER
T203	STORAGE FLUID TEMPERATURE--BOTTOM OF TANK	T651	CHILLED WATER RETURN TEMPERATURE
T250	STORAGE FLUID OUTLET TEMPERATURE	T652	COOLING WATER TEMPERATURE AT EXISTING COOLING TOWER INLET
T450	HOT FLUID RETURN TEMPERATURE	T653	COOLING WATER TEMPERATURE AT EXISTING COOLING TOWER OUTLET
T509	COOLING WATER TEMPERATURE AT COOLING TOWER INLET	T675	TEMPERATURE INSIDE BUILDING
T510	COOLING WATER TEMPERATURE AT COOLING TOWER OUTLET	W100	COLLECTOR LOOP FLOW RATE
T552	CHILLER FLUID TEMPERATURE AT CHILLER 2 OUTLET (OR) AT CHILLER 1 INLET	W400	HEATING LOOP FLUID FLOW RATE
T553	CHILLER FLUID TEMPERATURE AT CHILLER 1 OUTLET (OR) CHILLER FLUID SUPPLY TEMPERATURE	W502	CHILLER FLUID FLOW RATE TO RC/AC
T560	SOLAR FLUID TEMPERATURE AT RANKINE 1 BOILER INLET	W561	SOLAR FLUID FLOW RATE TO RANKINE 1
T561	SOLAR FLUID TEMPERATURE AT RANKINE 2 BOILER INLET	W562	SOLAR FLUID FLOW RATE TO RANKINE 2
T562	SOLAR FLUID TEMPERATURE AT RANKINE 1 BOILER OUTLET	W571	COOLING WATER FLOW RATE TO RANKINE 1 CONDENSER
T563	SOLAR FLUID TEMPERATURE AT RANKINE 2 BOILER OUTLET	W572	COOLING WATER FLOW RATE TO RANKINE 2 CONDENSER
T571	COOLING WATER TEMPERATURE AT RANKINE 1 CONDENSER OUTLET	W581	COOLING WATER FLOW RATE TO CHILLER 1 CONDENSER

Table C-1. SDAS Sensor Description (OTS 45) (Concluded)

SENSOR	DESCRIPTION	SENSOR	DESCRIPTION
W582	COOLING WATER FLOW RATE TO CHILLER 2 CONDENSER	EP571	ELECTRIC POWER DRAW BY RANKINE 1 CONDENSER PUMP (P9)
W600	CHILLER FLUID FLOW RATE TO LOAD	EP572	ELECTRIC POWER DRAW BY RANKINE 2 CONDENSER PUMP (P11)
EP100	CIRCULATING PUMP ELECTRIC POWER DRAW (PRIMARY)	EP581	ELECTRIC POWER DRAW BY CHILLER 1 CONDENSER PUMP (P10)
EP101	CIRCULATING PUMP ELECTRIC POWER DRAW (BACKUP)	EP582	ELECTRIC POWER DRAW BY CHILLER 2 CONDENSER PUMP (P12)
EP102	PURGE FAN ELECTRIC POWER DRAW	EP600	EXISTING 228T CHILLER ELECTRIC POWER DRAW
EP400	HEATING LOOP PUMP (P8) ELECTRIC POWER DRAW	EP601	EXISTING 228T CHILLER ELECTRIC POWER DRAW
EP401	EXISTING RADIANT HEATERS ELECTRIC POWER DRAW	EP603	EXISTING CHILLER FLUID PUMP (P3) POWER DRAW
EP402	EXISTING RADIANT HEATER ELECTRIC POWER DRAW	EP604	EXISTING CHILLER FLUID PUMP (P4) DRAW
EP403	EXISTING RADIANT HEATER ELECTRIC POWER DRAW	EP605	EXISTING COOLING TOWER FAN POWER DRAW
EP502	ELECTRIC POWER DRAW BY CHILLER FLUID PUMP (P5)	EP606	EXISTING CONDENSER PUMP (P2) POWER DRAW
EP507	POWER GENERATED BY RANKINE 1	EP607	EXISTING CONDENSER PUMP (P1) POWER DRAW
EP508	POWER GENERATED BY RANKINE 2	I001	SOLAR INSOLATION (PYRANOMETER)
EP510	ELECTRIC POWER DRAW BY COOLING TOWER		
EP511	AUXILIARY POWER FOR COOLING REQUIRED BY RANKINE 1 MOTOR		
EP512	AUXILIARY POWER FOR COOLING REQUIRED BY RANKINE 2 MOTOR		
EP513	ELECTRIC POWER DRAW BY COOLING TOWER		
EP521	PARASITIC POWER DRAW BY RANKINE 1		
EP522	PARASITIC POWER DRAW BY RANKINE 2		

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Figure C-1. Location of SDAS Sensors

APPENDIX D

UNCERTAINTY ANALYSIS OF SOLAR PERFORMANCE FACTORS

The uncertainty of determining the performance evaluation factors for a particular solar energy system is related to the data requirement accuracy for sensor signal conditioning, the data acquisition sampling rate and the data processing method [3]. An error analysis of the calculations of certain performance parameters for SRP, based only on sensor accuracies, was conducted and is presented here. Two methods in general use for combining precision errors in measuring several variables to estimate the error in the calculated performance factors are (1) absolute limits and (2) statistical bounds. The derivation and use of these methods is given in Reference [3]. The results of this analysis for SRP are presented in Table D-1. Notice that the measurement accuracy for the cooling load calculation was ± 18 percent. This happens because two discrete resistance bulbs are used to measure a small Δt drop across the chiller as opposed to using differential thermocouples on bridge-connected resistance bulbs.

Table D-1. Uncertainty Analysis Results

PERFORMANCE FACTOR	TOLERANCE OR UNCERTAINTY (PERCENT)
SOLAR COLLECTOR EFFICIENCY	± 10.8
HEAT RATE TO RANKINE BOILERS	± 7.7
RANKINE GENERATED SHAFT POWER	± 9.2
(RANKINE + AUXILIARY) POWER	± 5.2
COOLING PRODUCED	± 18.0
BUILDING COOLING LOAD	± 12.4
FRACTION SOLAR CONTRIBUTION TO COOLING LOAD	± 24
THE FOLLOWING SENSOR ACCURACIES WERE ASSUMED FOR ESTIMATING THE UNCERTAINTIES:	
TEMPERATURE	$\pm 0.50^\circ\text{F}$
FLOW RATE	± 3 PERCENT
POWER (EP SENSORS)	± 2 PERCENT
RANKINE EFFICIENCY	± 5 PERCENT