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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 44) at Ocmulgee National Monument, in Georgia, based on the analysis of data collected between April 1981 and August, 1981. The following topics are discussed: system description, performance assessment, operating energy, energy savings, system maintenance, and conclusions. The solar energy system at OTS 44 is a hydronic heating and cooling system consisting of 5040 square feet of liquid-cooled flat-plate collectors; a 4000-gallon thermal storage tank; one 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 for providing space conditioning and hot water to the building. Based on the instrumented test data monitored and collected during the 4 months of the Operational Test Period, the solar system collected 285 MMBtu of thermal energy of the total incident solar energy of 1040 MMBtu and provided 210 MMBtu for cooling and 10 MMBtu for heating and hot water. The net electrical energy savings due to the solar system was approximately 2600 kWh(e), and fossil energy saving was about 20 million Btu (MMBtu).

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Honeywell

August 1982

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - FINAL REPORT FOR HONEYWELL OTS 44, OCMULGEE, GEORGIA

DOE/NASA CONTRACTOR REPORT   DOE/NASA CR-

Prepared by

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Under Contract NAS8-32093

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

For the U.S. Department of Energy

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FOREWORD

The Solar Energy System Performance Evaluation has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. The analysis contained in this document describes the technical performance of an Operational Test Site (OTS) functioning throughout a specified period of time which is typically one season. The objective of the analysis is 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 of the Operational Test Site described in this document have been collected, processed and maintained under the OTS Development Program and have procided the major inputs used to perform the long-term technical assessment. The data have been archived by the Marshall Space Flight Cetner for the Department of Energy.

In July of 1976, Honeywell Energy Resources Center (Minneapolis, Minnesota) entered into a contract agreement with NASA's Marshall Space Flight Center to design and develop solar-powered building space heating and cooling systems. This ongoing engineering field test effort is known as the "404" program. The objectives of the program are the development and fielding of solar heating and cooling systems that (1) have efficient performance capabilities, (2) are low in cost, and (3) are 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, are subcontractors. Honeywell was responsible for the solar 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 their production flat plate solar collector.

Data collection and reduction was performed by Vitro Laboratories.

The solar-powered heating, cooling, and hot water system described in this report was installed at the Ocmulgee National Monument Visitor Center near Macon, Georgia. This site is identified as OTS-44 in the NASA/Honeywell "404" program operational test site listing. The system became operational in April 1981.

The mechanical equipment was installed in the basement of the visitor center and the collector array was installed adjacent to the visitor center. The system provides solar-derived heating and hot water and up to 25 tons of solar-assisted cooling. Gas-fired back-up units are available for times when there is insufficient solar energy to meet the heating and hot water loads. Cooling is accomplished through the use of a 25-ton Rankine engine-assisted water chiller. The system is also capable of power generation.

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SECTION 1.0

SYSTEM DESCRIPTION

The solar heating and cooling system at the Ocmulgee National Monument in Macon, Georgia, is a liquid-type system comprised of the following basic components:

- Lennox LSC18-1 flat plate liquid-type solar collectors (280 collectors, 5040 square feet gross area);
- Lennox 25-ton Rankine-assisted chiller;
- 4000 gallon water storage tank;
- Four air handling units with hydronic heating/cooling coils and fourteen fan coils units, supplied with chilled water from the chiller, or hot water from either solar storage tank or auxiliary boiler;
- Associated piping, pumps, controls and other equipment.

The Ocmulgee collector array is shown in Figure 1-1.

The solar heating and cooling system schematic is shown in Figure 1-2. The system provides solar heating in the form of solar-heated water from the solar storage tank and/or solar cooling in the form of chilled water to the building as determined by the solar control panel. These services are provided through four air handling units and fourteen fan coil units located in the building. The gas-fired boiler will provide backup auxiliary natural gas heat during the heating season and is available to satisfy any occasional heating requirements during the cooling season.

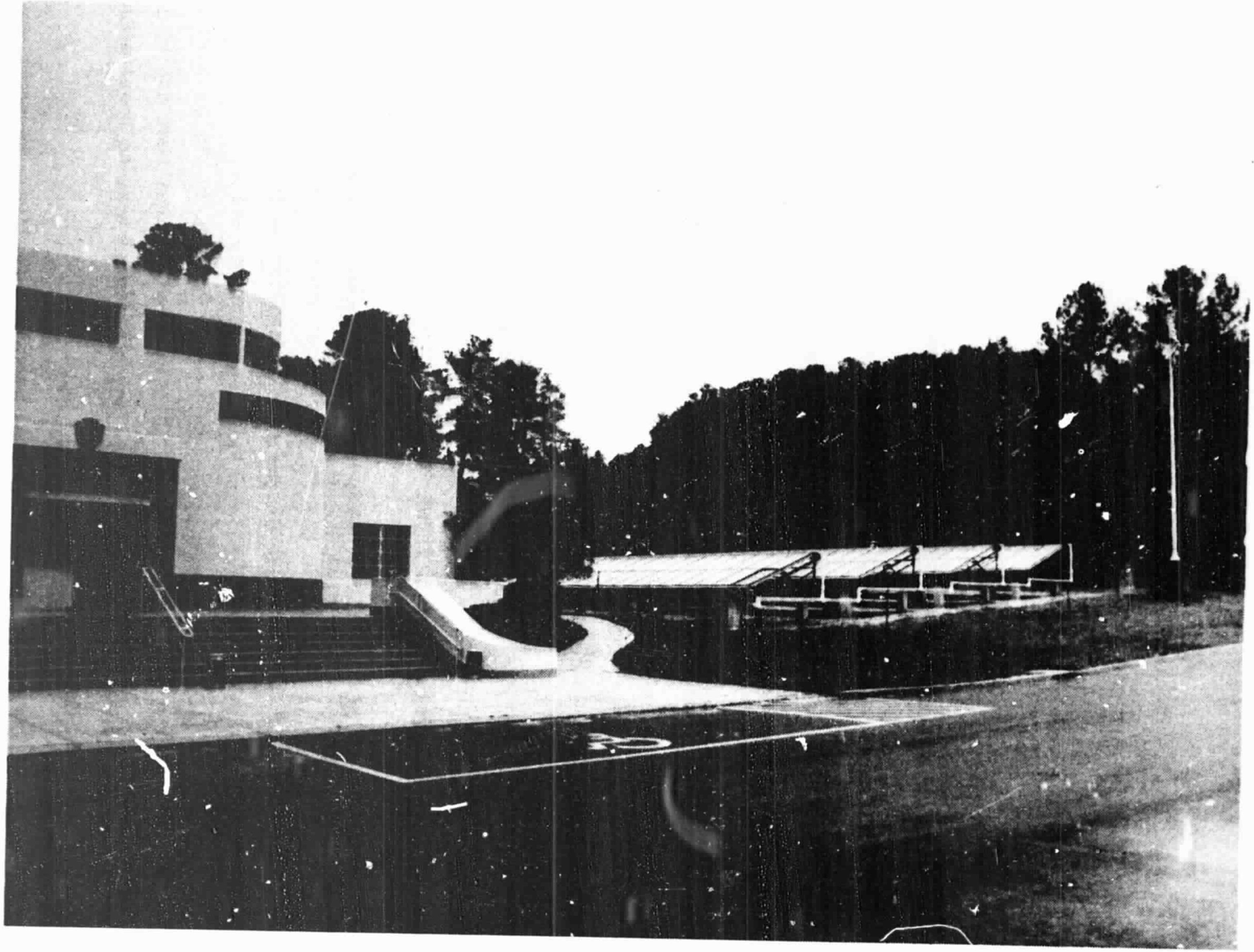
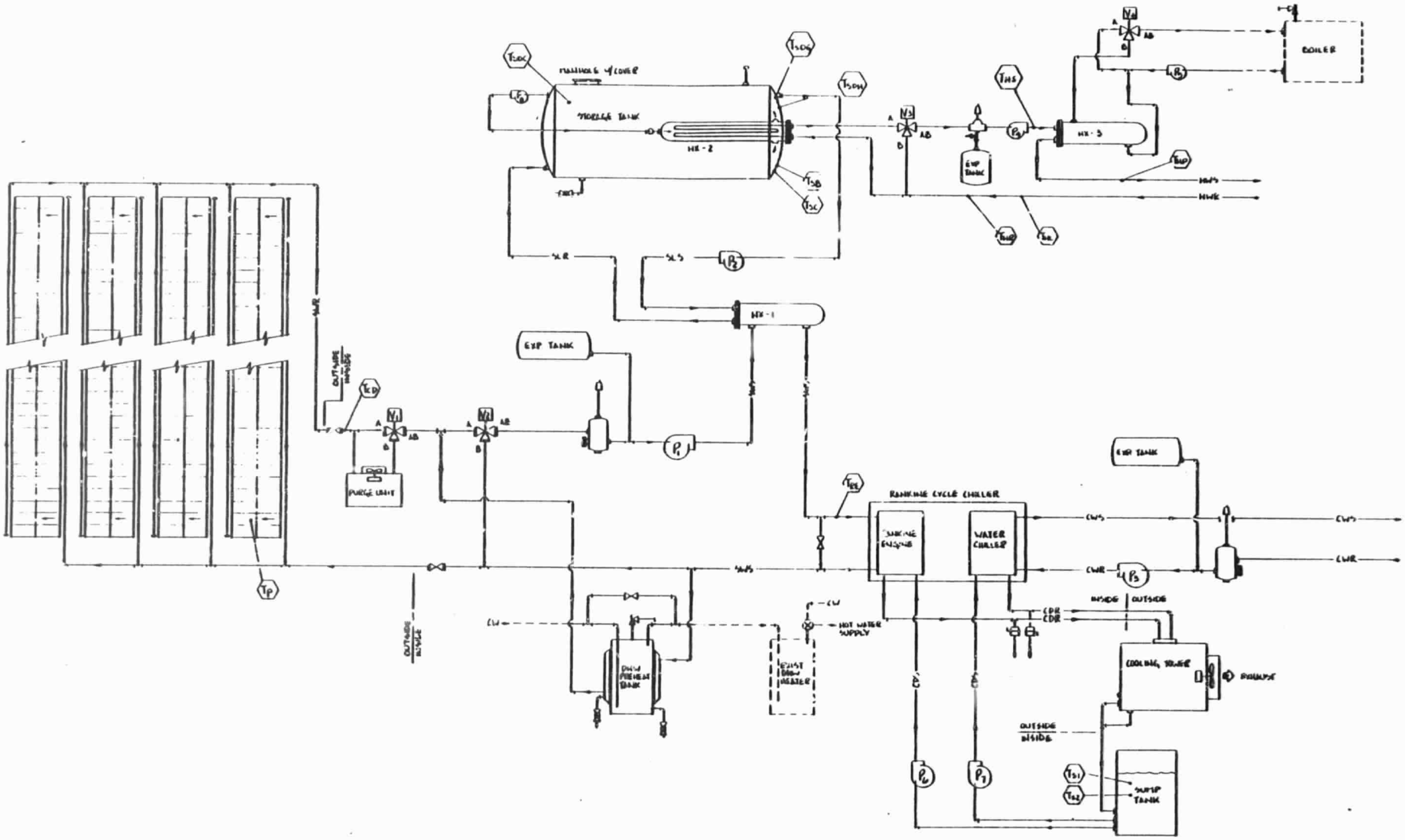


FIGURE 1-1. OCMULGEE COLLECTOR ARRAY



FIGUREZ 1-2. OCMULGEE HEATING AND COOLING SYSTEM SCHEMATIC

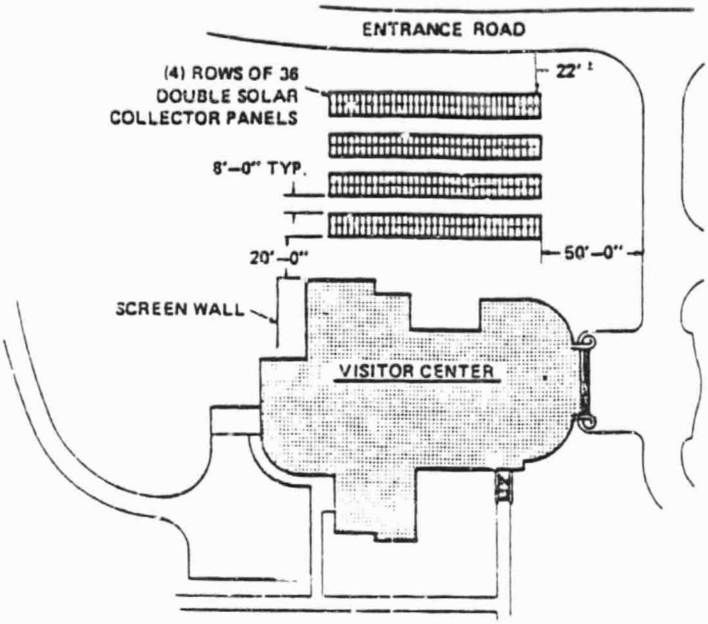


FIGURE 1-3. SITE LAYOUT

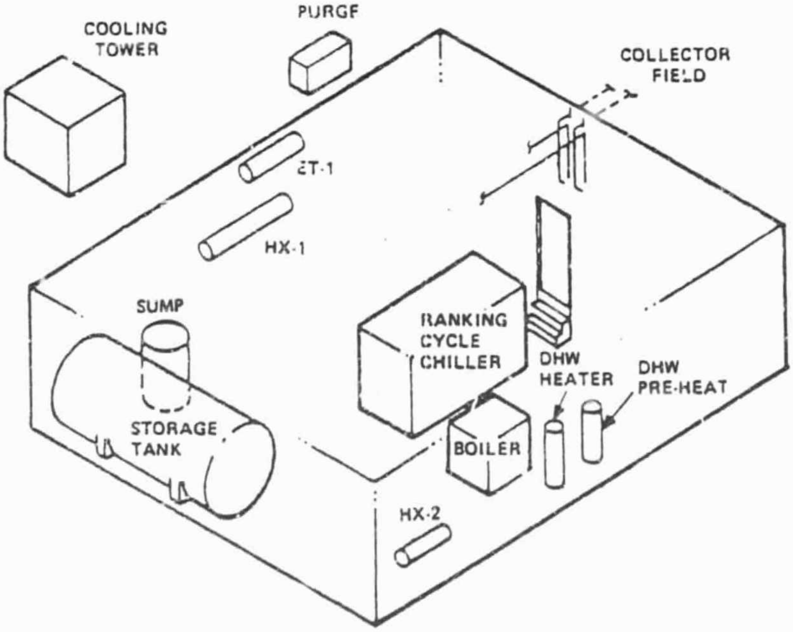


FIGURE 1-4. MECHANICAL ROOM

Figure 1-3 shows the relative layout of the building, collector array and mechanical room. The collectors are arranged in four rows, 35 collectors wide and two high, oriented 39^{0} west of south. The base of the collector support area is located on a hillside approximately 15 feet above the basement floor. The collector field is located approximately 20 feet from the mechanical room. All exterior piping is well insulated. The piping between the collector field and mechanical room is buried for protection.

The mechanical room (shown in Figure 1-4) is located in the Northwest corner of the building and contains the Rankine-assisted chiller, the 4000 gallon storage tank, a 40 gallon domestic hot water heater with an 80 gallon domestic hot water solar preheat tank, the gas fired auxiliary boiler and associated pumps, heat exchangers and piping. The cooling tower and purge unit are located outside the building on a concrete pad approximately ten feet above the mechanical room floor and two feet from the mechanical room wall.

1.1 SYSTEM OPERATING MODES

The solar heating and cooling system delivers solar heating in the form of solar-heated water and/or solar cooling in the form of chilled water to the building. All system modes of operation are controlled automatically by the solar control panel. The solar control panel takes inputs from the various sensors, aquastats and the building temperature control panel and, through relay logic, places the solar heating and cooling system into the proper mode of operation. Figure 1-5 shows the locations of all control sensors and aquastats in the system.

The system has nine modes of operation as follows:

- Direct Cooling from Collectors,
- Cooling from Storage,
- Electric Motor Auxiliary Cooling,
- Storage Charging,
- Heating from Storage,
- Auxiliary Heating from Boiler,
- Rankine Engine Power Generation,

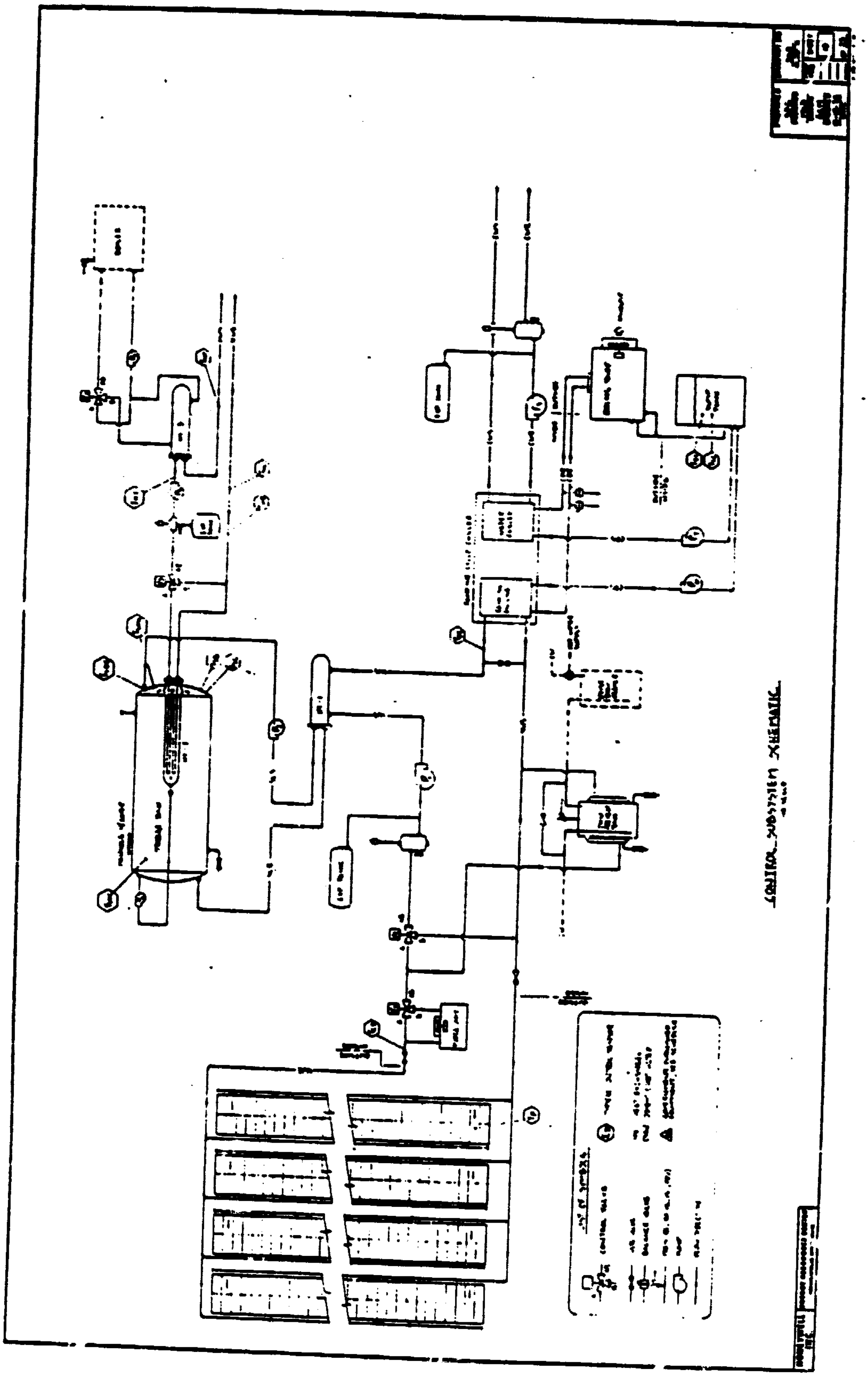


FIGURE 1-5. CONTROL SUBSYSTEM SCHEMATIC

- Purge Excess Energy,
- DHW Preheating.

1.1.1 Cooling Mode

A cooling demand from the Building Temperature Control Panel activates pump P3 to provide chilled water circulation. An internal thermostat and unload mechanism within the Rankine Cycle Chiller activates electric motor operation and capacity control. On a cooling demand, the cooling tower fan operates either on low speed or high speed as controlled by aquastats T_{S1} and T_{S2} located in the sump tank. Condenser water pump P7 is activated with the chiller.

The Rankine Engine will be activated if there is sufficient direct solar energy available from the collectors (Direct Cooling from Collectors). Pump P1 provides circulation from the collectors to the Rankine Engine.

If there is a cooling demand and no direct solar energy is available from the collectors, and sufficient stored solar energy is available from the Storage Tank, the Rankine engine will be activated (Cooling From Storage). Stored solar heat is provided to the Rankine Engine through operation of pumps P1 and P2 and heat transfer across heat exchanger HX-1. Collector loop flow is bypasses around the collectors by positioning control valve V2.

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 chiller compressor, the auxiliary electric motor will act as an electric generator, feeding power back into the electrical system. In order for electrical generation to occur, the motor must be excited by the electrical service to the unit. The unit cannot, therefore, generate electricity during a power outage. Condenser water pump P6 is activated in conjunction with the Rankine engine.

1.1.2 Heating Mode

Upon a heating demand from the Building Temperature Control Panel, pump P4 is activated to provide heating circulation. Whenever a significant temperature difference exists between the heating return water and the water in the Storage Tank, heating return flow is circulated thorugh tube bundle heat exchanger HX-2 in the Storage Tank for utilization of stored solar energy as directed by control valve V3 (Heating From Storage). Pump P8 provides storage fluid flow around the tube bundle to improve performance of heat exchanger HX-2.

If heating return water leaving heat exchanger HX-2 is below the loop design supply temperature of $120^{O}F$, auxiliary heat is added from the Boiler through circulation of pump P5 and heat transfer through heat exchanger HX-3. Modulation of control valve V4 controls the heating water supply temperature (Auxiliary Heating from Boiler).

1.1.3 Storage Charging Mode

If there is no demand for heating or cooling operation from the Building Temperature Control Panel, the system will be available for Storage Charging. Whenever a significant temperature exists between the Solar Collectors and the Storage Tank, the system will be activated for storage charging. This is accomplished through operation of pumps P1 and P2 and heat transfer across heat exchanger HX-1.

1.1.4 Generation Mode

If there is no demand for heating or cooling operation from the Building Temperature Control Panel and the Storage Tank is fully charged, the system will be available for Rankine Engine Power Generation. If sufficient solar energy is available from the collectors, pump P1 is activated, and a signal is sent to start the Rankine engine and de-couple the chiller compressor via the electric clutch.

The auxiliary electric motor will act as an electric generator, feeding power back into the electrical system. In order for electrical generation to occur, the motor must be excited by the electrical service to the unit. The unit cannot, therefore, generate electricity during a power outage. Condenser water pump P6 is activated in conjunction with the Rankine Engine.

1.1.5 Purge Excess Energy

For over-temperature protection, the system will purge excess energy if the collector loop temperature becomes excessively high. Operation of control valve V1 and activation of the Purge Unit fan will cause purging. Purge cycle operation is available in any mode of operation.

1.1.6 Domestic Hot Water Preheating

All domestic hot water provided to the building passes through the Domestic Hot Water Preheater before entering the conventional hot water heater. Solar energy is transferred to the entering domestic water through a wrap around heat exchanger on the DHW preheater. Flow through the heat exchanger is provided during operation of pump P1 when valve V2 is in the A - AB position.

Additional heat is added at the conventional hot water heater if required.

1.2 TYPICAL SYSTEM OPERATION

The Ocmulgee system had two basic operating seasons. During the cooling season the system cools (direct and from storage), preheats domestic hot water, generates electricity, and charges storage. During the heating season the system provides space heating, preheats domestic hot water, and charges storage.

The following sections detail the system operation for a typical day during the heating and cooling seasons.

1.2.1 Heating Season Operation

Figure 1-6 shows typical collector array inlet and outlet temperatures during heating season operation (February 5, 1981). During heating season operation the system is activated for energy collection when the difference between the collector absorber plate temperature and the storage tank temperature reaches 18°F. Storage charging operation began at 1103 and continued until 1516. Storage charging stops when the difference between the absorber plate temperature and the storage tank temperature falls to 3°F. Comparing Figures 1-6 and 1-7 it can be seen that the drop in the collector array outlet temperature starting at about 1400 hours coincided with a drop in the available insolation (Figure 1-7). The insolation rose again at 1527 and storage charging operation resumed at 1543 and continued until 1604. The hot water preheat tank is charged whenever there is flow through the collector array.

Figure 1-8 shows typical storage tank temperatures for heating season operation. The storage tank sat idle until 0718 when heating operation began. Stratification of the storage fluid is apparent when there is no storage charging. Heating from storage ended at 0953. Storage charging began at 1103. Heating from storage was resumed at 1343. There was simultaneous storage charging and heating from storage from 1343 to 1516 and from 1543 to 1604.

At the end of storage operation the temperature of the storage fluid began to stratify. As shown in Figure 1-8, the temperature at the top (T201) and middle (T202) of the storage tank declined in a nearly linear fashion. The temperature at the bottom of the tank (T203) did not drop linearly. This indicates that the thermal stratification pattern in the storage tank changed with time.

During the heating season there is normally a 140°F upper limit for storage charging. However, during the 1908-81 heating season the chiller was disabled and the Rankine engine was allowed to generate electricity when sufficient solar energy was available and the storage tank was fully charged. During the "generate" season the storage tank is charged beyond the normal 140°F limit.

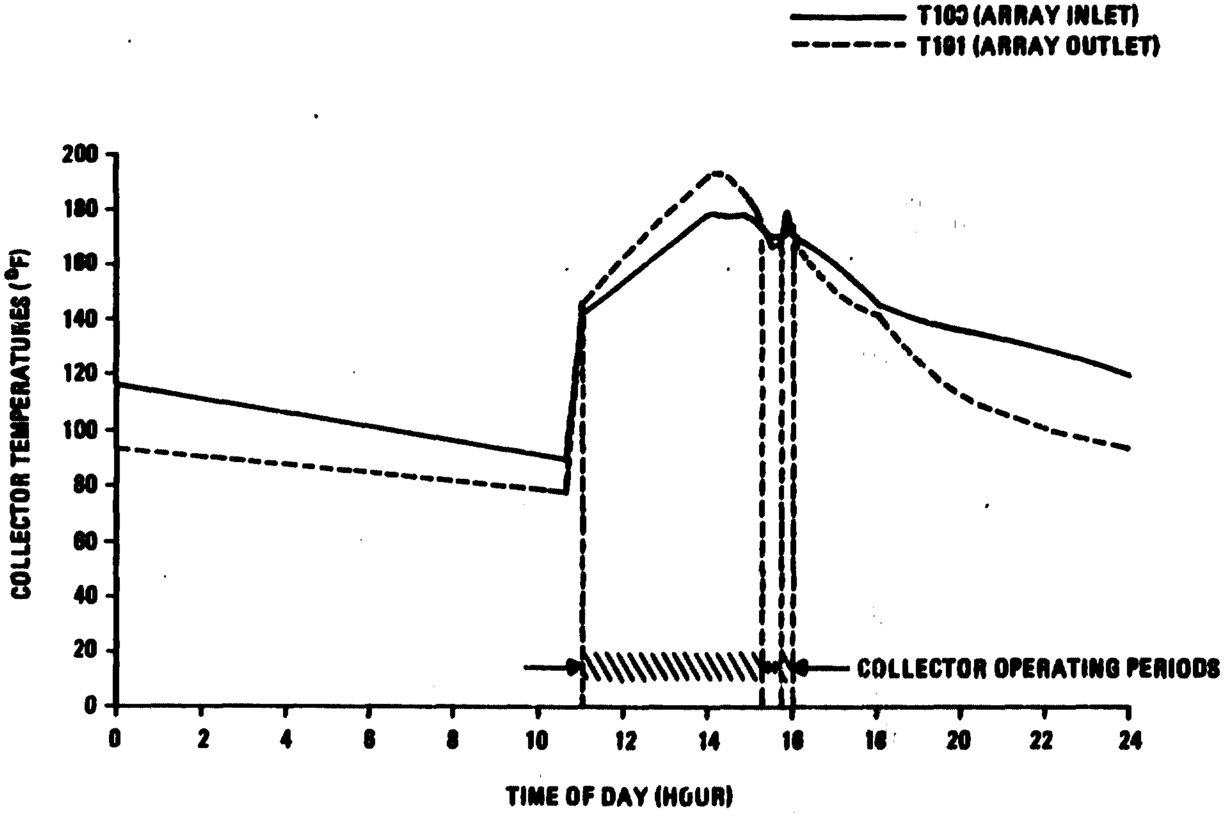


FIGURE 1-6. COLLECTOR ARRAY TEMPERATURES vs. TIME OF DAY, HEATING SEASON (2/5/81)

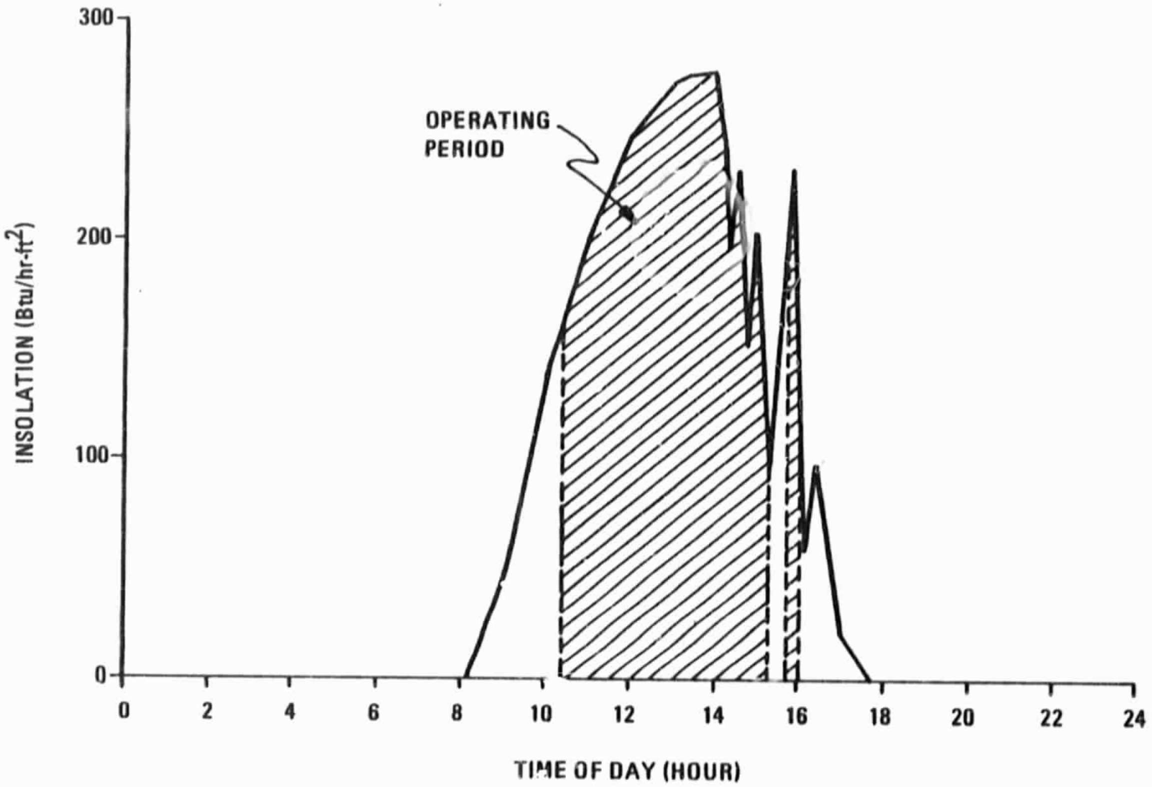


FIGURE 1-7. AVAILABLE SOLAR INSOLATION vs. TIME OF DAY, HEATING SEASON (2/5/81)

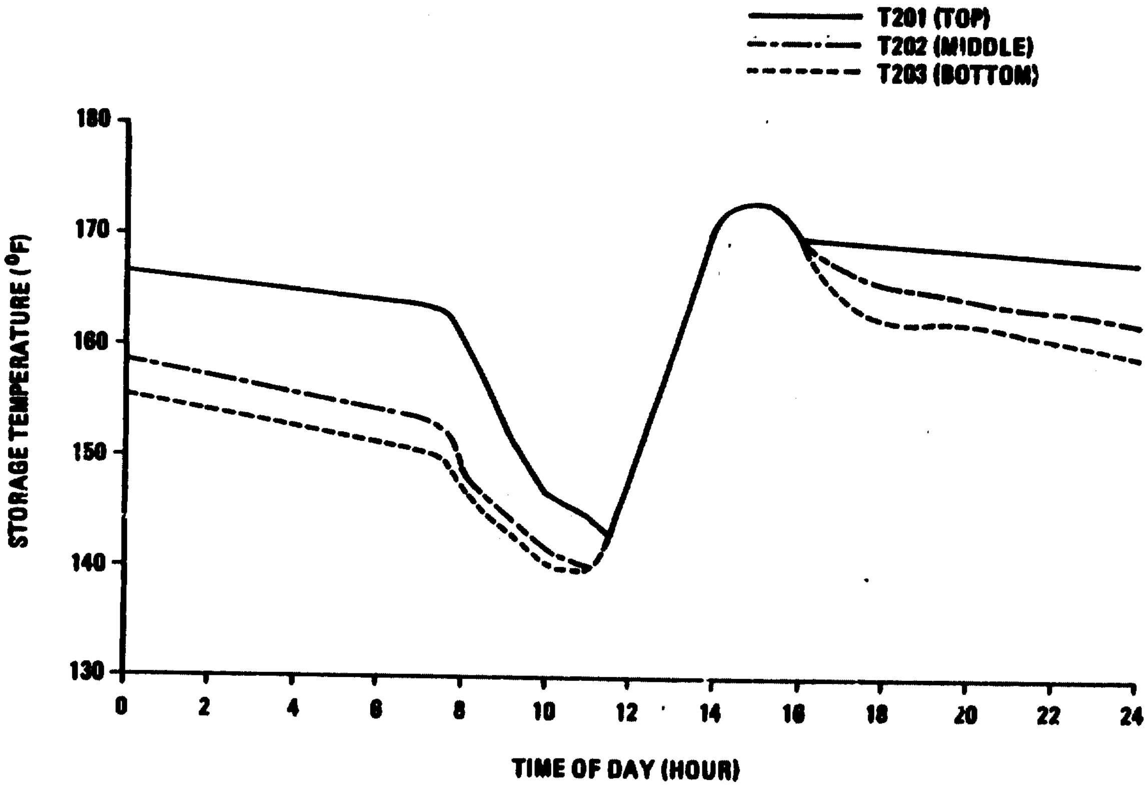


FIGURE 1-8. STORAGE TANK TEMPERATURES vs. TIME OF DAY, HEATING SEASON (2/5/81)

2.3.2 Cooling Season Operation

Figure 1-9 shows typical collector array inlet and outlet temperatures and available insolation during cooling season operation (May 23, 1981). The collector array inlet temperature sensor, T100, is also the Rankine engine outlet temperature sensor. There were three periods of cooling from storage as shown by peaks in the array inlet temperature at 0736, 0813, and 0851. At 0917 the collector panel absorber plate temperature reached the operating set point of 170°F and fluid was circulated through the collector array. The warm fluid in the collector array was displaced by the cooler fluid in the system piping. When the cooler fluid reached the absorber plate temperature sensor the flow through the collector array was stopped. After ten minutes the absorber plate temperature has again reached 170°F and flow is directed through the collector array. This process continued until all of the fluid in the collector loop is at 170°F. On this day (5/23/81) the system was cooling from storage and the majority of the collector loop fluid was already at 150°F. Therefore, only one iteration of the on/off sequence was necessary to raise the fluid to 170°F. On days when cooling from storage does not precede collector loop operation this on/off sequence may be repeated two or more times.

The drop in the collector array inlet and outlet temperatures at 1317 was due to purge unit activation. The purge unit was activated to reject energy to the environment when the fluid temperature reached 215°F.

Figure 1-10 shows typical storage tank temperatures during cooling season operation. The system cooled from storage for three twenty-minute periods at 0731, 0813, and 0851. Storage was charged from 1622 until 1649, after there was no demand for cooling.

The Rankine engine inlet and outlet temperatures are shown in Figure 1-11. There were four periods of Rankine engine operation throughout the day. The first three periods were cooling operation utilizing stored thermal energy. Rankine operation direct from the collector array began at 0955 and continued until 1612. The drop in the temperature at 1323 was due to purge unit operation. There was a small amount of electricity generated just before and just after purge unit operation.

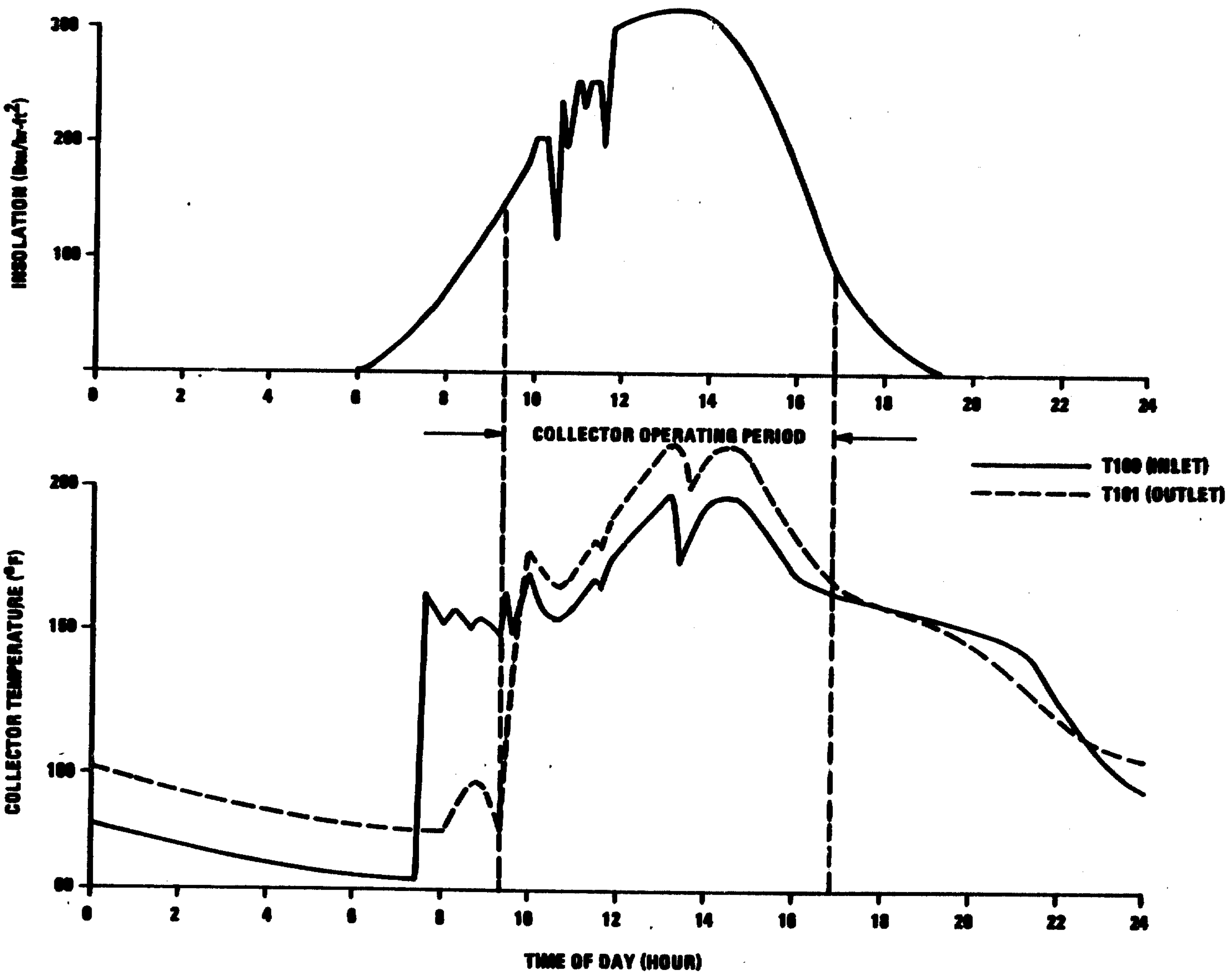


FIGURE 1-9. COLLECTOR ARRAY TEMPERATURES AND INSOLATION vs. TIME OF DAY, COOLING SEASON (5/23/81)

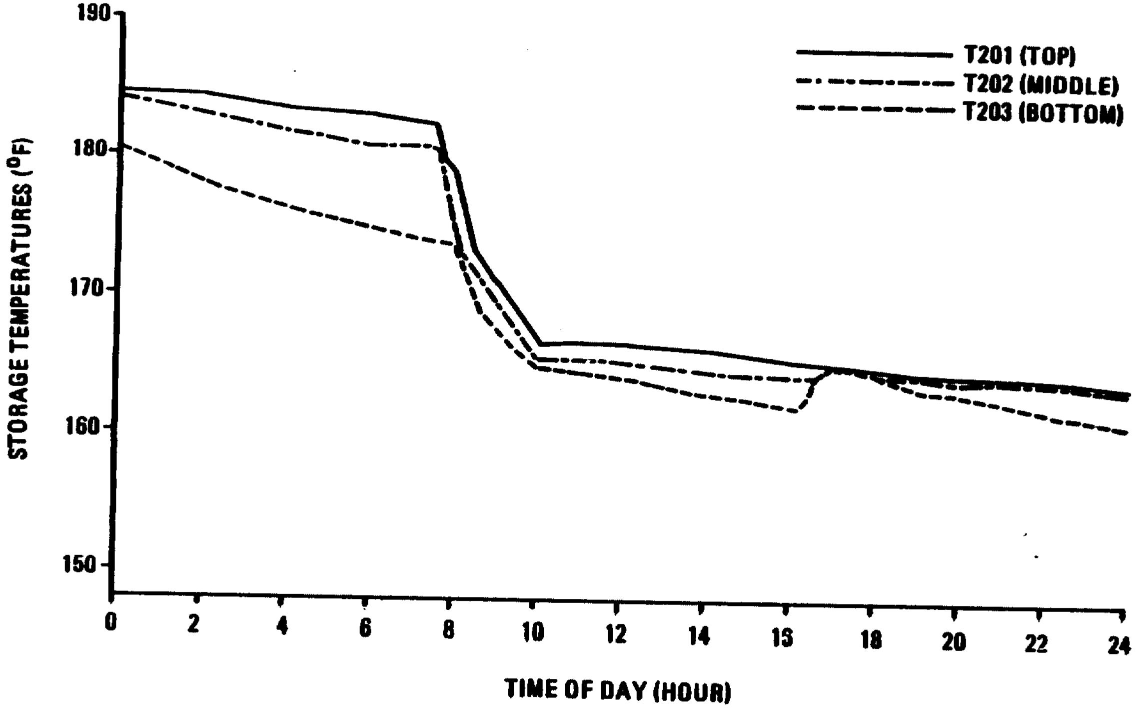


FIGURE 1-10. STORAGE TANK TEMPERATURES vs. TIME OF DAY, COOLING SEASON (5/23/81)

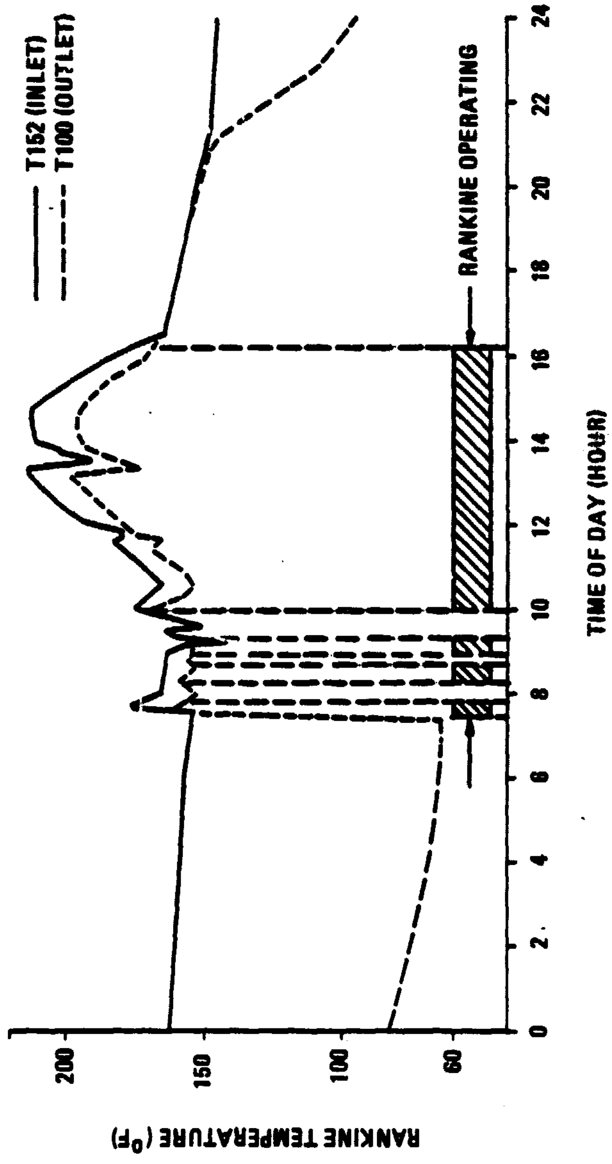


FIGURE 1-11. RANKINE ENGINE TEMPERATURES vs. TIME OF DAY (5/23/81)

Figure 1-12 shows the auxiliary electricity used by the chiller motor. During the hours of peak solar conditions the Rankine engine supplied most of the shaft input necessary to drive the chiller to satisfy the cooling load.

1.3 SYSTEM OPERATING SEQUENCE

The system at Ocmulgee has two distinct operating seasons as mentioned in Section 1.2. The following sections outline the system operating sequence during the heating and cooling seasons.

1.3.1 Heating Season Operating Sequence

The operation of the space heating subsystem is controlled by the building space thermostat. If the stored thermal energy is not able to meet the heating load the auxiliary gas-fired boiler is activated. When there is sufficient difference between the collector absorber plate temperature and the storage tank temperature the collector array is activated for energy collection. The collected energy is transferred to the storage tank via a tube and shell heat exchanger. If there is no heating load, the storage tank is fully charged, and the Rankine engine is enabled the system will generate electricity. The system preheats hot water whenever there is collector loop operation. Auxiliary hot water heating is available from a gas-fired back-up unit.

This sequence of operation is shown in Figure 1-13 for February 5, 1981. There was simultaneous solar and auxiliary heating from 0718 to 0953 and 1343 to 1620 and auxiliary-only heating from 1620 to 1735. All solar energy collected was transferred to the storage tank. There were occasional periods of auxiliary hot water heating throughout the day.

1.3.2 Cooling Season Operating Sequence

The operation of the space cooling subsystem is controlled by the building space thermostat. Upon a call for cooling, the auxiliary electric motor is activated to drive the vapor compression water chiller. If solar energy

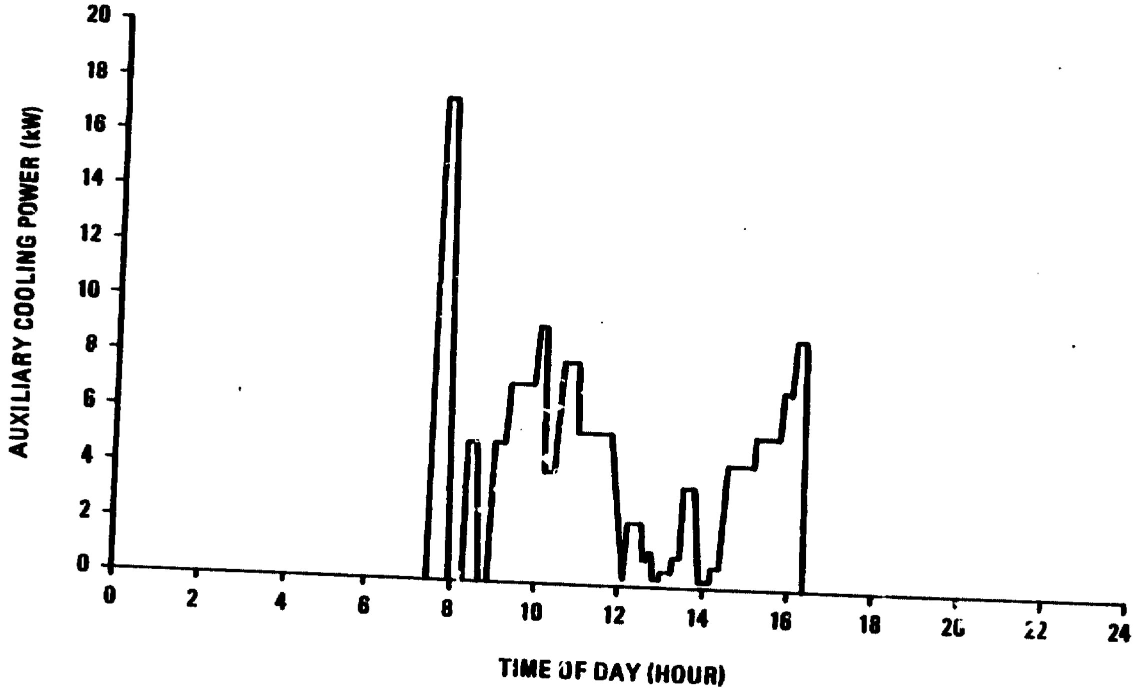


FIGURE 1-12. AUXILIARY ELECTRICITY USED vs. TIME OF DAY (5/23/81)

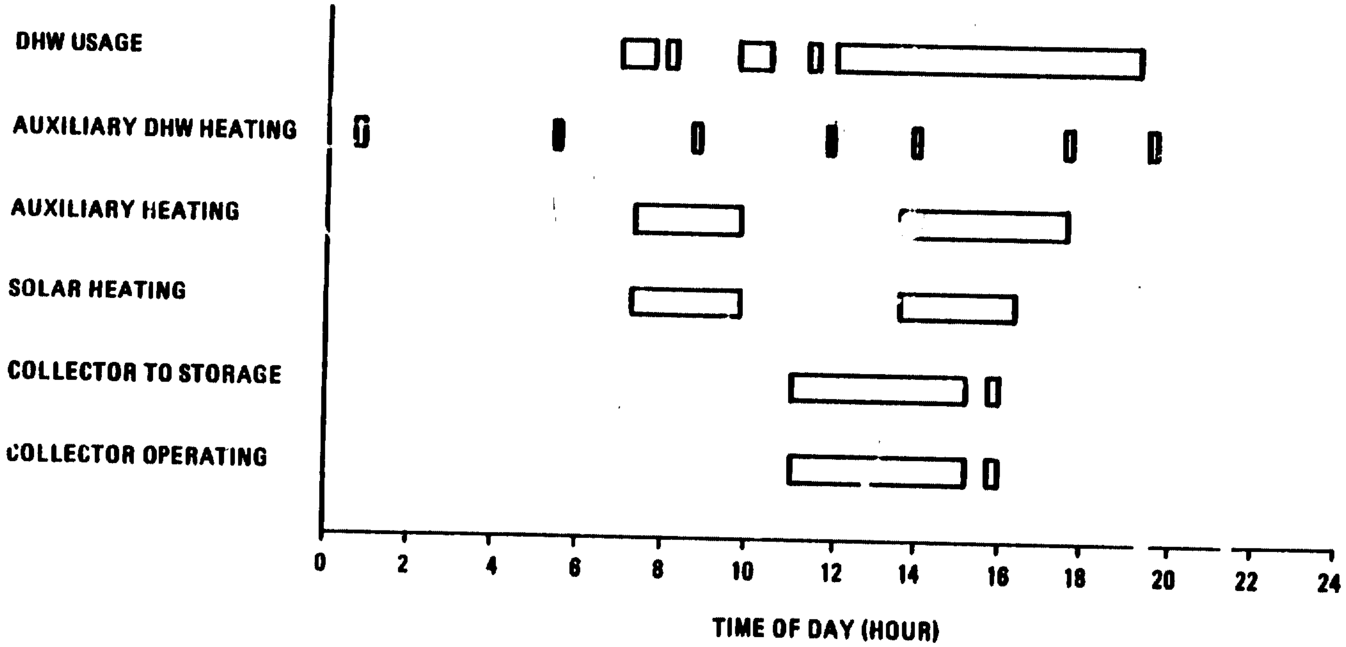


FIGURE 1-13. TYPICAL HEATING SEASON OPERATING SEQUENCE (2/5/81)

is available directly from the collector array the Rankine engine will be activated to unload the auxiliary electric motor. If there is no solar energy available from the collector array and there is sufficient energy in the storage tank the system will operate the Rankine from storage to unload the auxiliary electric motor. If solar energy is not available from either source the chiller will continue to be driven by the auxiliary electric motor. If there is no cooling load the system will charge storage. As with heating season operation, the system preheats hot water whenever the collector loop is active.

The system is also capable of power generation. During direct cooling if the amount of solar energy supplied to the Rankine is greater than is necessary to meet the cooling load the Rankine will drive the axuiliary motor as a generator. If there is no cooling load and the storage tank is fully charged the clutch between the motor and the chiller will disengage and the Rankine engine will drive the motor as a generator.

The above sequence of operation is shown in Figure 1-14. Prior to collector array operation the system ran the Rankine engine from storage to download the auxiliary electric motor for three twenty-minute periods at 0736, 0813, and 0851. At 0955 there was sufficient solar energy to activate the Rankine engine and the system operated in the direct solar-assisted cooling mode until 1612. At that time ther was no cooling load and the system charged storage until 1649. During ther periods of peak solar insolation the Rankine engine was able to supply all of the shaft input necessary to drive the chiller and generated some electricity, as indicated by the shaded areas.

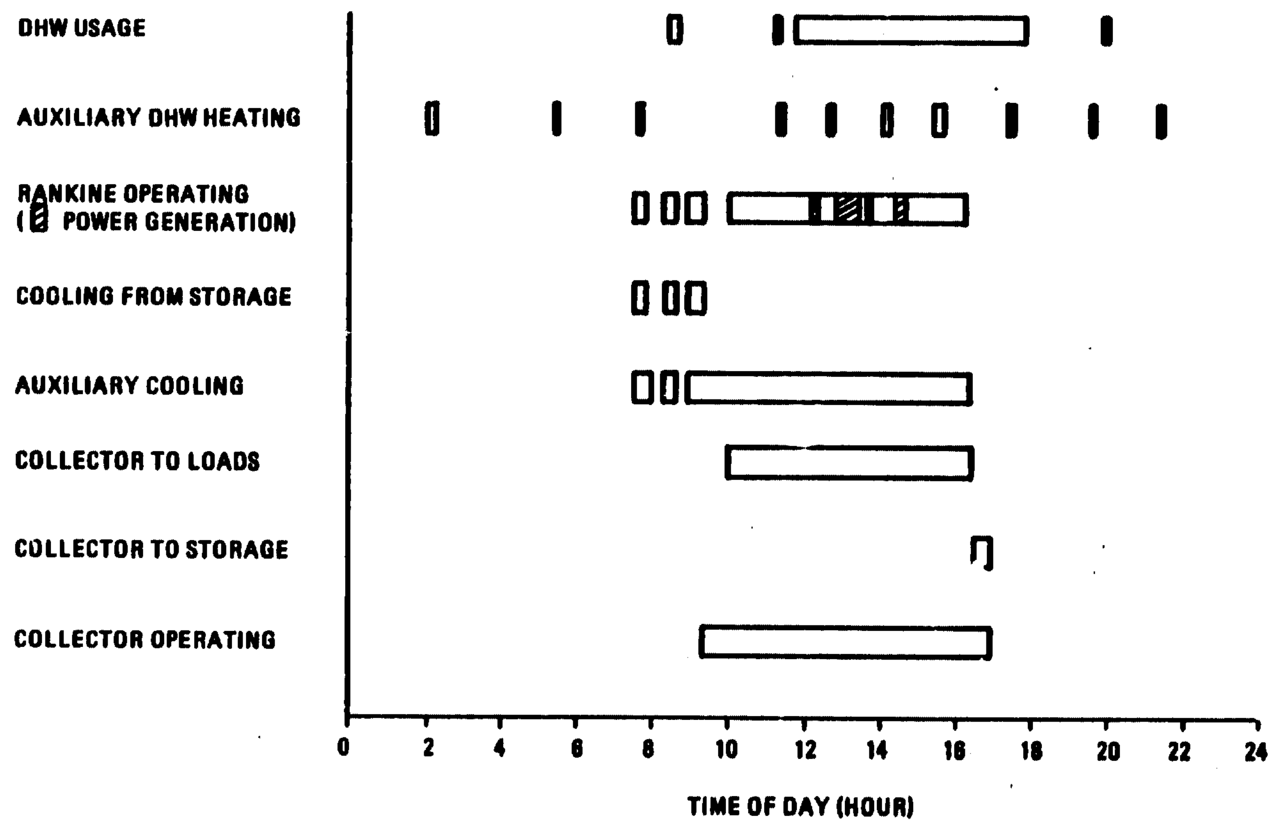


FIGURE 1-14. TYPICAL COOLING SEASON OPERATING SEQUENCE (5/23/81)

SECTION 2.0

PERFORMANCE ASSESSMENT

The Operational Test Period (OTP) for the Ocmulgee solar heating and cooling system extended from April 1, 1981, to August 31, 1981. 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
  - Domestic Hot Water
  - 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 lists the sensors used to monitor the performance of the system; shows the locations within the system of all sensors; and escribes 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 C. 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 (see Appendix D). 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 August 1981). 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 34 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 delivered to hot water subsystem to provide hot water usage, purged (intentionally rejected to environment), or lost to the environment. As shown in the figure, the greatest portion (70 percent) of collected energy was delivered to the Rankine boilers. Of this, 98 percent was used for cooling and 2 percent was used for generation. About one percent of collected energy was used to support hot water subsystem. Collected energy delivered to thermal storage to provide for space heating and cooling accounted for 18 percent; of this 1 percent of collected energy was used for heating and about 2 percent of collected energy was used for cooling; the remaining 15 percent were storage losses. Purged energy was estimated to be 6 percent of the collected energy.

Most of the energy purging occurred when the Rankine engine was inoperable. The system energy losses were estimated to be about 5 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

The subsection presents the results of analyzing the monthly data available for the six subsystems -- collector, storage, hot water, 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 system--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 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 Ocmulgee collector array collected 25 percent of all the solar energy incident upon it and 32 percent of the solar energy incident during collector operation. Based on the instrumentation error analysis presented in Appendix D the collector efficiencies calculated from measured data have an uncertainty of ± 10.6 percent. The efficiencies are based on gross collector area.

TABLE 2-1. SYSTEM PERFORMANCE SUMMARY

MONTH AND YEAR	AVERAGE DAILY INSOLATION IN THE PLANE OF THE COLLECTOR ARRAY		AVERAGE AMBIENT TEMPERATURE		SYSTEM LOAD			SOLAR FRACTION OF THE SYSTEM LOAD			NET ENERGY SAVINGS	
	MEASURED (Btu/Ft²-Day)	LONG-TERM AVERAGE (Btu/Ft²-Day)	MEASURED (°F)	LONG-TERM AVERAGE (°F)	HOT WATER (MMBtu)	SPACE HEATING (MMBtu)	SPACE COOLING (MMBtu)	HOT WATER (PERCENT)	SPACE HEATING (PERCENT)	SPACE COOLING (PERCENT)	FOSSIL FUEL (MMBtu)	ELECTRICAL ENERGY [kWh(e)]
APRIL 1981	1742	1776	69	66	3.7	5.9	39.4	73	51	32	9.5	760
MAY 1982	1714	1818	70	74	3.8	0	31.6	80	0	41	5.0	790
JUNE 1981	1736	1804	82	80	3.7	0	91.9	78	0	14	4.8	470
JULY 1981	1590	1700	83	81	0.8	0	104.5	13	0	16	0.2	560
AUGUST 1981	1308	1710	78	81	0.5	0	79.5	35	0	1	0.2	-30
TOTAL	8090	8808	—	--	12.4	5.9	346.9	72	51	—	19.7	2550
AVERAGE	1618	1762	76	76	3.7[a]	5.9[b]	69.4	77[a]	51[b]	16	6.6[a]	645[c]

(a) Average does not include July and August 1981; DHW subsystem had problems

(b) Seasonal average

(c) Average does not include August 1981; Rankine engine and collector subsystem experienced problems.

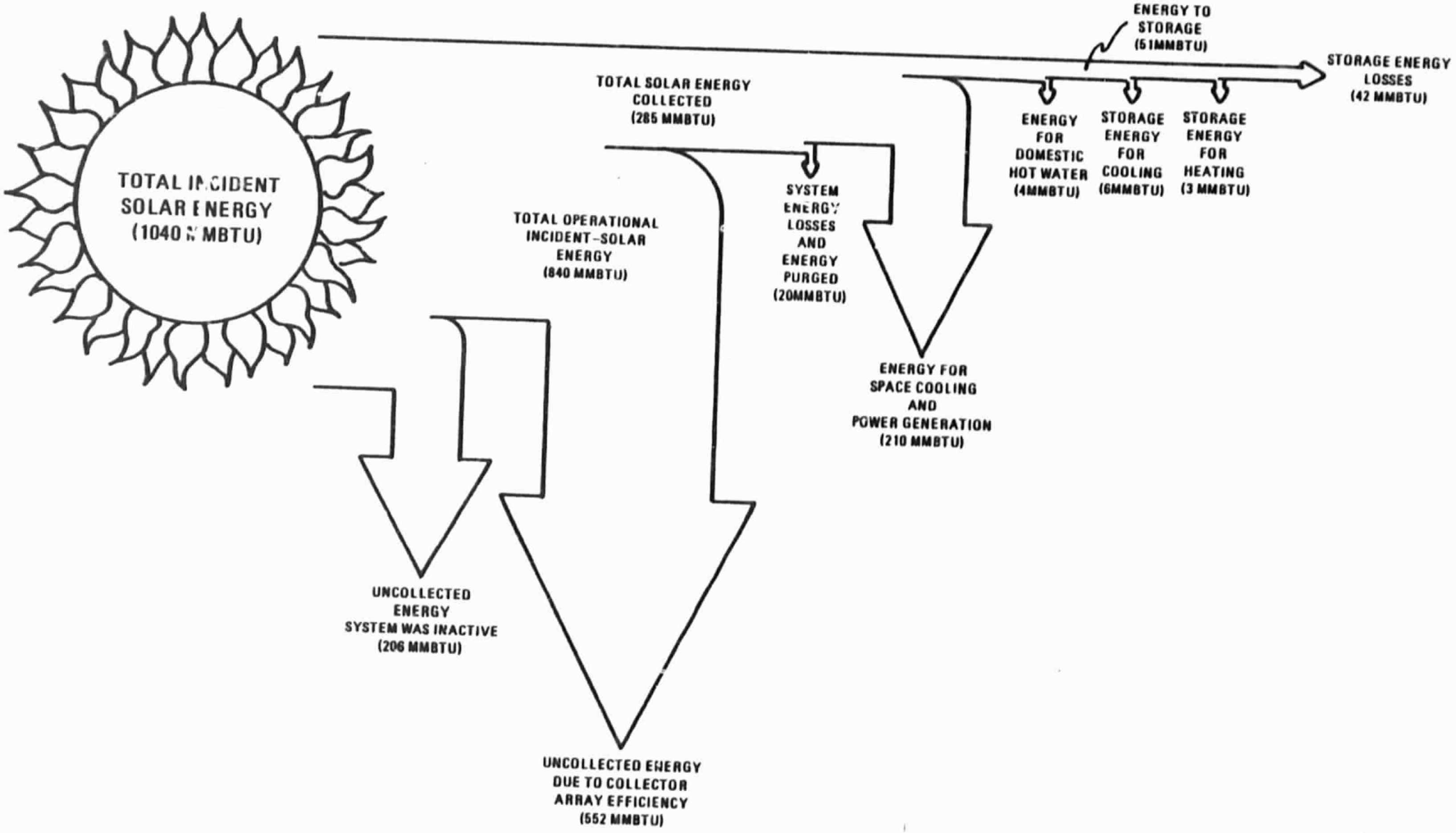


FIGURE 2-1. SYSTEM TEST PERIOD* SOLAR ENERGY USE

*Four months of OTP (April, May, June and July 1981)

TABLE 2-2. COLLECTOR ARRAY PERFORMANCE

	INCIDENT SOLAR ENERGY (10^6 Btu)	SOLAR ENERGY COLLECTED (10^6 Btu)	COLLECTOR ARRAY EFFICIENCY (Percent)	OPERATIONAL INCIDENT ENERGY (10^6 Btu)	OPERATIONAL COLLECTOR ARRAY EFFICIENCY (Percent)
APRIL	263	76	29	220	35
MAY	268	72	27	211	34
JUNE	262	75	29	216	35
JULY	249	61	24	189	32
AUGUST	204	26	13	124	21
TOTAL	1246	310	--	960	—
AVERAGE	249	62	25	192	32

During the first two weeks in August 1981 the system pump was not operational due to a leaky metal seal. Therefore, the collector array efficiency during the month was low. The collectors stagnated during this time. Also, the operational collector efficiency was lower than expected. The collectors were observed to be heavily soiled. The collectors were cleaned in the first week of September. Whether collector stagnation or soiling were the cause for low operational collector efficiency could not be determined a data was not available. However, our experience with other systems indicat~ that collector stagnation does not affect the collector efficiency significantly.

The array did better based on an instantaneous basis. Figure 2-2 depicts the inverse dependency of the instantaneous collector effiency on the operating point. The operating point is defined as:

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

where,

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

All points for calculation of the measured collector efficiencies were taken within ± 1 hour of noon and when the solar insolation was steady. 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 <u>gross</u> collector area during system operation. All points for calculation of measured collector efficiency were taken within ± 2 hours of noon.

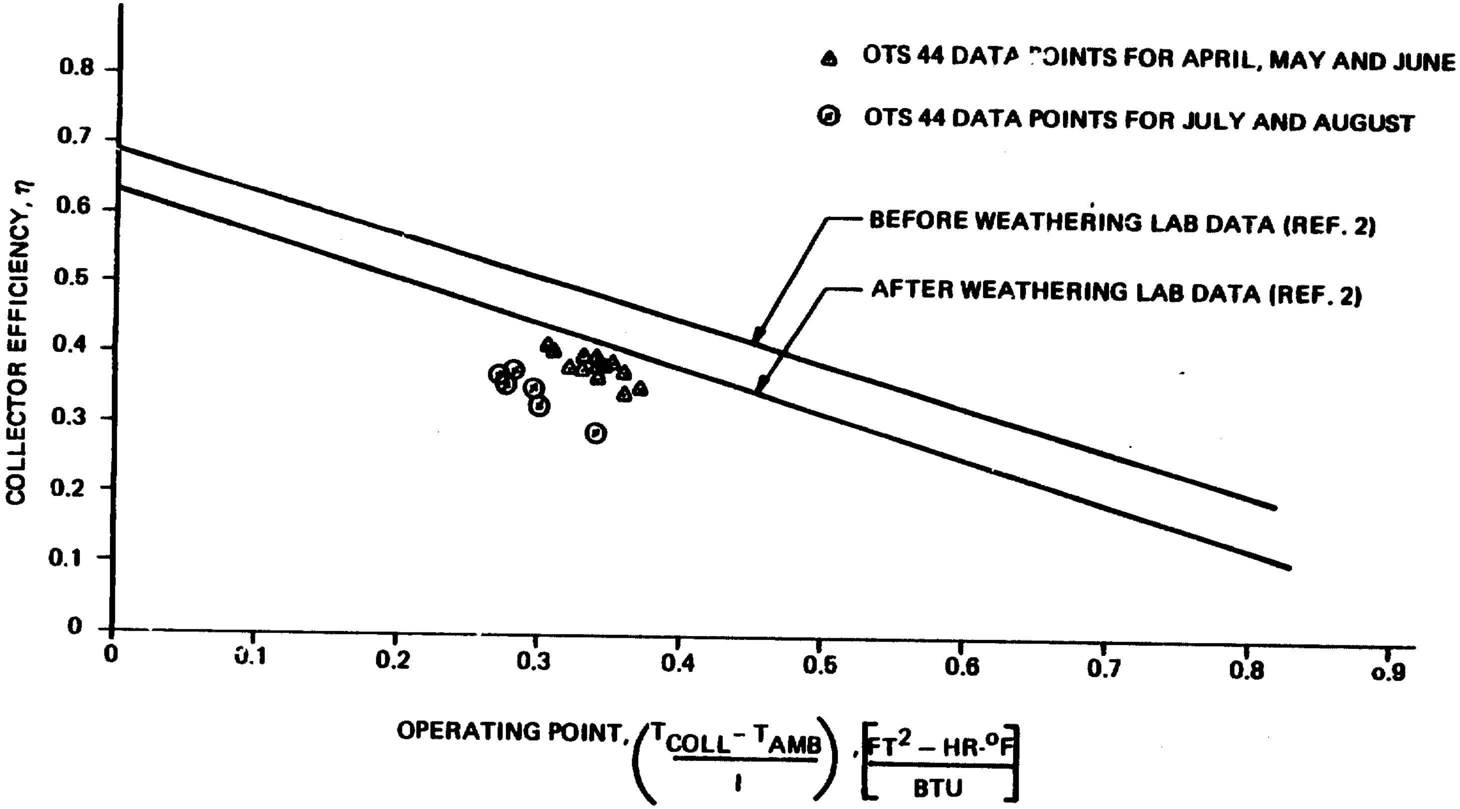


FIGURE 2-2. COLLECTOR EFFICIENCY vs. OPERATING POINT

As shown the collector efficiency was lower than the after weathering efficiency. Also the efficiency decreased with time over the operational test period due to soiling. The collectors were cleaned in early September but data was not available to indicate any imporvement in efficiency.

2.2.2 Storage Performance

The thermal storage tank consists of a 4000 gallon capacity steel tank with a 0.012 inch layer of corrosion resistant lining. The entire tank is surrounded by a rectangular studded wall (floor to ceiling), the interior of which is filled with fiberglass insulation. The tank is filled with 3800 gallons of water with a corrosion inhibitor to prevent oxide corrision.

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.

The performance of the storage subsystem during April, when there was a heating load, was typically better than the rest of the test period. During the cooling season, storage is utilized for space cooling and storage charging occurs when there is no cooling demand or the Rankine system is not operational and if the storage temperature is less than the collector fluid temperature. During most of the cooling season in the test period not enough solar solar energy was available to keep the storage charged to temperatures above 170°F. The storage temperature should be above 170°F for the storage cooling mode to be activated. Also, high storage temperatures result in high storage energy

TABLE 2-3. STORAGE SUBSYSTEM PERFORMANCE

MONTH	ENERGY IN STORAGE (10^6 BTU)	ENERGY FROM STORAGE (10^6 BTU)	CHANGE IN STORED ENERGY (10^6 BTU)	STORAGE HEAT LOSS (10^6 BTU)	STORAGE EFFICIENCY (Percent)	STORAGE AVERAGE TEMPERATURE (°F)	STORAGE HEAT LOSS COEFFICIENT (Btu/hr-Ft^2 F)
APRIL 1981	14.4	5.2	+0.55	8.7	40	150	0.38
MAY 1981	15.8	2.0	+0.18	13.6	14	166	0.43
JUNE 1981	11.7	0.9	-0.34	11.1	5	161	0.42
JULY 1981	9.4	1.6	-0.25	8.1	14	152	0.36
AUGUST 1981	12.9	0.2	+1.66	11.0	14	153	0.41
TOTAL	64.2	9.9	+1.80	52.5	13	—	—
AVERAGE	12.8	2.0	+0.4	10.5	13	156	0.42

losses. Therefore, during the cooling season the storage efficiencies are typically low as is evident from Table 2-3. (Even if the storage was kept fully charged and utilized for storage cooling during non-solar hours, the maximum storage efficiency would have been 60 percent. It would have taken more than half the collected energy to keep the storage fully charged.)

The measured heat loss coefficient was about 0.4 Btu/hr-ft^2-F. In calculating the heat loss coefficient the tank area and temperature differential between bulk fluid and ambient was utilized. The storage heat loss calculated from the difference between energy charged to and discharged from storage and adding the net change in stored energy includes the heat loss from storage tank and the heat loss in the piping to and from the storage tank and temperature sensor location on the piping.

2.2.3 Domestic Hot Water (DHW) Subsystem Performance

The domestic hot water subsystem consists of a 82 gallon DHW preheat tank with a jacket type heat exchanger. All domestic hot water delivered to the building on demand passes through the DHW preheat tank before entering the conventional 40 gallon gas fired DHW heater. The preheated water is provided to the DHW tank whenever there is flow through the collection field such as during storage charging or direct Rankine operation.

Measured monthly performance parameters for the DHW subsystem are listed in Table 2-4. Solar energy supplied 72 percent of the hot water load. The hot water demand at the site was low and to simulate the demand an automatic load device was installed. Therefore, the load in April, May and June were high due to the artificial demand. The load device was taken out in the last week of June. Problems with the pressure/temperature relief valves on the DHW preheat tank caused water to be ramdomly released during the OTP.

TABLE 2-4. HOT WATER SUBSYSTEM PERFORMANCE

MONTH	ENERGY SUPPLIED			HOT WATER LOAD		AVERAGE DAILY WATER USAGE (Gals.)	HOT WATER STANDBY LOSSES (10^6 Btu)	SOLAR FRACTION OF LOAD (Percent)
	AUXILIARY (10^6 Btu)	AUXILIARY THERMAL (10^6 Btu)	SOLAR (10^6 Btu)	LOAD (10^6 Btu)	WATER USAGE (Gallons)			
APRIL 1981	1.7	1.0	2.7	3.7	5340	178	(a)	73
MAY 1981	1.2	0.7	3.1	3.8	8650	268	(a)	80
JUNE 1981	1.4	0.8	2.9	3.7	6260	208	(a)	78
JULY 1981	1.1	0.7	0.1	0.8	208	7	0.6	13
AUGUST 1981	0.5	0.3	0.2	0.5	300	10	0.3	35
TOTAL	4.4	3.5	8.9	12.4	20758	671	(a)	72
AVERAGE	0.9[(b)]	0.8[(b)]	2.9[(b)]	3.7[(b)]	6750[(b)]	218[(b)]	(a)	77[(b)]

(a) Data for hot water demand not available

(b) Average for April, May and JUne.

2.2.4 Space Heating Subsystem

Solar thermal energy stored in the storage tank us used to supply part of the space heating load. A shell and tube heat exchanger, located inside the storage tank, transfers heat from hot water in the storage tank to the heating loop. A conventional gas fired boiler makes up the difference between the space heating demand and that supplied by the storage tank. Another shell and tube heat exchanger is used as a heat transfer interface between the heating loop and the boiler loop (see Figure 1, system schematic).

The performance parameter of the space heating subsystem is listed in Table 2-5. The only space heating load during the OTP was 5.9 million Btu during April. Generally, early morning ambient temperatures were low enough till mid-April to require some space heating, but, at sunrise, ambient temperatures elevated quickly, requiring space cooling shortly thereafter. The space heating subsystem solar fraction was 51%. The fraction could have been significantly higher had the storage tank temperatures been greater on April 9 through April 13 when space heating was required. Storage tank temperatures were low at mid-month because the storage charging mode was sacrificed for the direct cooling mode from the collectors.

2.2.5 Space Cooling Performance

The space cooling subsystem consists of the one 25-ton Rankine engine air conditioner (R/C-A/C). The Rankine unit used solar energy when available; otherwise it used auxiliary electrical energy. 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 unit is discussed in the following section.

Measured monthly performance parameters for the space cooling subsystem are listed in Table 2-6. The significant cooling load occurred in June and July 1981. Over the entire cooling season, during the OTP, 31 percent of the building cooling load was met while the Rankine engines were actually operating. Of this, 29 percent was during the period when solar energy was supplied direct from collectors and one percent during cooling from storage mode. The

TABLE 2-5. SPACE HEATING SUBSYSTEM PERFORMANCE

MONTH	SPACE HEATING LOAD	ENERGY SUPPLIED (10^6 Btu)		SOLAR FRACTION (PERCENT)	AVERAGE AMBIENT TEMPERATURE (°F)
		SOLAR	AUXILIARY THERMAL		
APRIL 1981	5.9	3.0	2.9	51	69
MAY 1981	0.0	0.0	0.0	-	70
JUNE 1981	0.0	0.0	0.0	-	82
JULY 1981	0.0	0.0	0.0	-	83
AUGUST 1981	0.0	0.0	0.0	-	78
TOTAL	5.9	3.0	2.9	51	-
AVERAGE	5.9	3.0	2.9	51	76

TABLE 2-6. SPACE COOLING SUBSYSTEM PERFORMANCE

MONTH	COOLING LOAD			SOLAR FRACTION OF LOAD	SOLAR ENERGY USED		AUXILIARY ELECTRIC FUEL			AMBIENT TEMPER-ATURE	DAYTIME AMBIENT TEMPER-ATURE
	TOTAL (10^6 Btu)	DURING DIRECT COOLING (10^6 Btu)	DURING COOLING FROM STORAGE (10^6 Btu)	(PERCENT)	DIRECT FROM COLLECTORS (10^6 Btu)	FROM STORAGE (10^6 Btu)	TOTAL (10^6 Btu)	DURING SOLAR COOLING (DIRECT) (10^6 Btu)	DURING STORAGE COOLING (10^6 Btu)	(°F)	(°F)
APRIL 1981	39.4	19.5	0.65	32	54.8	2.4	6.6	2.0	0.09	69	81
MAY 1981	31.6	18.3	0.75	41	53.9	2.0	4.9	1.5	0.15	70	82
JUNE 1981	91.9	26.1	0.79	14	43.4	8.9	17.6	3.7	0.14	82	94
JULY 1981	104.5	37.7	1.65	16	51.6	1.6	19.2	5.7	0.30	83	95
AUGUST 1981	79.5	1.8	0.30	1	2.0	0.2	17.0	0.4	0.06	78	87
TOTAL	346.9	103.4	4.14	16	205.7	5.8	65.3	13.7	0.74	-	-
AVERAGE	66.9(a)	25.4(a)	1.0(a)	21(a)	50.9(a)	1.5(a)	12.1(a)	3.3(a)	0.17(a)	76	88

(a) The average was calculated excluding August 1981. August was not a representative month because several system problems were encountered during the month.

solar system was not operational for most of August 1981. Therefore, in any subsequent discussion August will be excluded. The averages in Table 2-6 do not take into account performacne during August. Based on this, 40 percent of the cooling load was met while the Rankine engine was actually operating; the solar contribution was calculated to be 21 percent.

The solar cooling fraction was calculated as the ratio of the total turbine work output (cooling only) to the sum of the turbine output and the motor output. The motor shaft output was estimated as the product of the electrical energy used and the motor efficiency. the turbine output was calculated as the product of the Rankine-cycle thermal efficiency and the solar energy used by the Rankine engine. The thermal efficiency was estimated from a lookup table as a function of solar inlet temperature and condenser sump temperature (see Subsection 2.2.6). However, the Rankine engine efficiency was lower than expected during most of OTP, as will be discussed in subsequent section. The actual solar contribution was lower than reported in Table 2-6.

The coefficient of performance, defined as the ratio of cooling load to auxiliary energy used, shows an increase through the OTP in the auxiliary mode. For example, from Table 2-6, in April, the cooling load and auxiliary usage, in auxiliary mode, were 19.3 MMBtu and 4.5 MMBtu(e), respectively. The COP is calculated to be 4.3. Similarily the COP's for subsequent months May, June, July and August is 4.3, 4.7, 4.9 and 4.6. The slight increase in COP since June was due to the decrease in temperature setting for the cooling tower fan. The cooling tower fan initially operated on the low speed setting with the temperature sensing aquastat monitoring condenser water to the tower at 85°F, and later at the high speed setting with the condensor water at 90°F or greater. The high and low speed temperature settings were decreased by 5°F during June 1981.

2.2.6 Rankine Cycle Engine and Air Conditioner

In the cooling season solar energy is converted to a 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 of the water chiller through an electric clutch. In this configuration, the motor may run the compresor 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 purging the energy.

The performance of the Rankine units installed at Ocmulgee was measured in the laboratory before shipping and installation. At design conditions of 195°F solar inlet temperature and 85°F condenser water inlet temperature, this (Rankine engine and chiller) producted 24 tons of cooling. The engine efficiency at these conditions was measured to be 7.9 percent. The vapor compressor COP's for the unit, defined as the cooling output to the shaft power input, was 5.2 at the design chilled water inlet temperature of 55°F.

The RC/AC performances for each month of operation is shown in Table 2-7. About 98 percent of the solar energy to the Rankine boilers was used to provide cooling and the remaining 2 percent was used for power generation.

The Rankine engine efficiency reported in Table 2-7 was 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. The Rankine engine normally did not operate as high as predicted during most of the OTP. Analysis of the data indicated that the thermal efficiency was about 65 percent of the predicted efficiency. The precise cause of the degraded engine performance is not known.

TABLE 2-7. RANKINE CYCLE SUMMARY

MONTH	SOLAR ENERGY TO RANKINE			RANKINE ENGINE EFFICIENCY(a) (PERCENT)	AUXILIARY ELECTRIC ENERGY [10^6 Btu(e)]	OPERATING ENERGY		GENERATED ELECTRICAL ENERGY [10^6 Btu(e)]	COOLING PRODUCED (10^6 Btu)	SOLAR FLUID TEMPERATURE (°F)
	TOTAL (10^6 Btu)	COOLING (10^6 Btu)	GENERATION (10^6 Btu)			COOLING [10^6 Btu(e)]	GENERATION [10^6 Btu(e)]			
APRIL 1981	59.4	57.2	2.2	6.8	6.6	5.4	0.2	0.18	39.4	185
MAY 1981	59	55.9	3.1	7.1	4.9	3.7	0.2	0.16	31.6	182
JUNE 1981	44.4	44.4	0.0	7.1	17.6	7.3	0	0.0	91.9	188
JULY 1981	53.2	53.2	0.0	6.8	19.2	7.4	0	0.0	104.5	180
AUGUST 1981	2.3	2.3	0.0	5.9	17.0	5.4	0	0.0	79.5	170
TOTAL	218.3	213.0	5.3	-	65.3	29.2	0.4	0.34	346.9	-
AVERAGE	54.0(b)	52.7(b)	1.3	7.0	12.1(b)	6.0(b)	0.1	0.07	66.9(b)	180

(a) Obtained from a look-up table using solar fluid inlet temperature to Rankine and condenser water temperature.

(b) Average for April, May, June and July.

Based on the data for cooling in the auxiliary mode, (no Rankine operation) presented in Table 2-6, the vapor compressor COP for the cooling season was calculated to be 5.2. This is calculated by dividing the cooling load during auxiliary mode by the product of auxiliary energy used in auxiliary mode and the motor efficiency (0.9). This is close to the expected performance.

The operating energies presented in Table 2-7 represent the electrical energy that was used to operate the solar loop pumps and to support the RC/AC "parasitics" (internal pumps, condenser fan and controls). The operating energy does not include the furnace fan, which was included in the cooling operating energy presented in Section 3.0. The operating energy was included in the table to provide complete information on the RC/AC performance characteristics.

SECTION 3.0

OPERATING ENERGY

For the solar heating and cooling system to porvide domestic hot water and space conditioning, electrical energy was required to operate the pumps, fans, valves and controls within the system. Operating energy (system total or subsystem usage) is thus defined as the electrical energy used by the system to perform those functions that did not directly influence the thermal state of the system and 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 because their power usage was very low.

Table 3-1 lists the operating energy consumed by the system and its subsystems during each month of the test period. The domestic hot water subsystem required no operating energy. The energy collection and storage subsystem (ECSS) operating energy is the energy used by the system to collect and store solar energy when the Rankine engine is not operating. It includes the purge unit operating energy. The space heating operating energy includes the air handling units (AHU), fans and solar heating pumps energy usage. The space cooling operating energy consists of all energy used to support the cooling subsystem, including the fan and the system pump P1 and is not the same as the values presented in Table 2-7, which are defined differently. The cooling subsystem operating energies are broken down into direct cooling mode, storage cooling mode and auxiliary mode. In the direct cooling mode, solar energy direct from collectors is used by Rankine engine to provide part of shaft power required by vapor compressors. The operating energy in this mode include system pump P1, R/C-A/C parasitics chiller pump, Rankine and chiller condenser pumps cooling tower fans and AHU and fan energy. The operating energy in the storage cooling mode (energy to Rankine provided from storage) includes system pump P1 storage pump P2, chiller pump, condenser pumps, cooling tower fans, and R/C-A/C parasitics and AHW and fan energy. The operating energy in auxiliary cooling mode includes the A/C condenser pump, chiller pump, cooling fan and AHW and fan energy. The total system system operating energy includes all electrical energy consumed by

TABLE 3-1. SYSTEM OPERATING ENERGY

MONTH	ECSS(a) OPERATING ENERGY [10^6 Btu(e)]	SPACE COOLING OPERATING ENERGY				SPACE HEATING OPERATING ENERGY [10^6 Btu(e)]	ENERGY GENERATION OPERATING ENERGY [10^6 Btu(e)]	TOTAL SYSTEM OPERATING ENERGY	
		TOTAL [10^6 Btu(e)]	AUXILIARY(b) COOLING [10^6 Btu(e)]	DIRECT(b) COOLING [10^6 Btu(e)]	STORAGE(b) COOLING [10^6 Btu(e)]			TOTAL [10^6 Btu(e)]	SOLAR SPECIFIC [10^6 Btu(e)]
APRIL 1981	0.9	7.7	1.7	2.5	0.1	0.8	0.04	9.4	2.3
MAY 1981	0.8	5.9	1.0	2.4	0.1	0	0.02	6.7	2.1
JUNE 1981	1.0	9.4	3.9	2.5	0.1	0	0	10.4	2.1
JULY 1981	0.6	9.4	3.6	3.3	0.1	0	0	10.0	2.3
AUGUST 1981	0.6	7.3	4.8	0.2	0.0	0	0	7.9	0.4
TOTAL	3.9	39.7	15.0	10.9	0.5	0.8	0.06	44.4	9.2
AVERAGE	0.8	7.9	3.0	2.2	0.1	0.8(c)	0.01	8.9	1.8

(a) Energy collection and storage subsystem operating energy; includes storage charging pump, purge unit and system pump during storage charging and purging only.

(b) Does not include operating energies for air handling units and fan power.

(c) Seasonal Average

the system except that used for auxiliary energy. It includes power generation and purge fan operating energies but is not credited for power generation, which appears only in electrical energy savings in the next section.

The total operating energy in the solar assist mode includes operating energies in direct cooling mode, storage cooling mode, solar heating mode, electric energy generation mode and ECSS operating energy. The solar specific operating energy includes operating energy used by system pump P1 storage pump P2, heating pump P8, purge fan and R/C parasitics, Rankine condenser pump P6 and part of cooling tower fan energy calculated using the ratio of rejected energy by Rankine to total thermal energy rejected in cooling tower.

The subsystem operating energy by mode presented in this section can be combined with the contribution to load by mode presented in Section 2 for each subsystem, to provide a subsystem performance measure by mode and also to calculate actual energy savings which is presented later in Section 4.

Over the test period, the system used 44.4 x 10^6 Btu of electrical (operating) energy to meet the system load of 365 x 10^6 Btu (12.4 x 10^6 Btu of DHW load, 5.9 x 10^6 Btu of space heating load and 347 x 10^6 Btu of space cooling load). This operating energy was used to support the use of both solar and auxiliary energy.

The total solar specific operating energy was 9.2 x 10^6 Btu(e). Note that this does not include the fan energy. The total solar contribution to the system load was 67.4 x 10^6 Btu (calculated from Table 2-1). The total solar energy collected was 310 x 10^6 Btu and that delivered to load subsystems was 230 x 10^6 Btu.

SECTION 4.0

ENERGY SAVINGS

Whenever solar energy is used instead of or in addition to auxiliary energy, energy savings are realized. The energy saved by the Ocmulgee solar heating and cooling system was determined by comparison of the energy used by the system with the energy that would have been required by assumed conventional load subsystems. The assumed conventional subsystems are the system's auxiliary load subsystems (gas hot water heater, gas fired furnace and motor-driven air conditioner), which are capable of meeting the entire house load. Energy used by components common to the solar and conventional subsystems (such as the air handling units, fans, chiller pump, and the air conditioner condenser) was ignored because of their commonality. The energy used to support the solar collection, sotrage and delivery was necessarily debited against the energy savings. The power generated was credited to the energy savings. Energy savings were both electrical and fossil.

The electrical energy savings and fossil energy savings for the system during the OTP are listed in Table 4-1. These are calculated as follows:

$$\text{(Electrical Energy Savings)} = \underbrace{\frac{\text{(Solar energy used for cooling)} \times \text{(Rankine Engine Efficiency)}}{\text{(Motor Efficiency = 0.9)}}}_{\text{Space cooling gross electric energy savings}} - \text{(Energy Generated by Rankine Subsystem)} - \text{(Solar Specific Operating Energy)}$$

$$\text{(Fossil Energy Savings)} = \frac{\text{(Solar Energy Used for Space Heating)}}{\text{(Furnace Efficiency = 0.6)}} + \frac{\text{(Solar Energy used for DHW)}}{\text{(DHW heater efficiency = 0.6)}}$$

TABLE 4-1. ENERGY SAVINGS

MONTH	GROSS ELECTRICAL ENERGY SAVINGS			FOSSIL FUEL ENERGY SAVINGS			SOLAR SPECIFIC OPERATING ENERGY [10^6 Btu(e)]	NET ELECTRICAL ENERGY SAVINGS [10^6 Btu(e)]	NET FOSSIL FUEL ENERGY SAVINGS [10^6 Btu]
	TOTAL [10^6 Btu(e)]	SPACE COOLING [10^6 Btu(e)]	ENERGY GENERATION [10^6 Btu(e)]	TOTAL [10^6 Btu]	SPACE HEATING [10^6 Btu]	DHW [10^6 Btu]			
APRIL 1981	4.9	4.7	0.2	9.5	5.1	4.4	2.3	2.6	9.5
MAY 1981	4.8	4.6	0.2	5.0	0	5.0	2.1	2.7	5.0
JUNE 1981	3.7	3.7	0	4.8	0	4.8	2.1	1.6	4.8
JULY 1981	4.2	4.2	0	0.2	0	0.2	2.3	1.9	0.2
AUGUST 1981	0.3	0.3	0	0.2	0	0.2	0.4	-0.1	0.2
TOTAL	17.9	17.5	0.4	19.7	5.1	14.6	9.2	8.7	19.7
AVERAGE	3.6	3.5	0.1	3.9	1.0	2.9	1.8	1.7	3.9

The fossil energy used in the auxiliary mode was natural gas. To compute the cubic feet of natural gas savings fossil energy savings are divided by the heating value of natural gas (= 1014 Btu/ft^3). Over the 7 months of the test period the net fossil energy savings were 19.7 MMBtu (= 19400 cubic feet of natural gas) while the net electrical energy savings were 2550 kWh.

The monetary savings for the test period is calculated to be $250. For calculating monetary savings the cost of natural gas was assumed to be $0.50 per hundred cubic feet and the cost of electricity was assumed to be $0.06 per kWh.

To compute the gross electrical energy savings for the cooling subsystem, Rankine engine efficiencies are required. The Rankine engine efficiencies used were from a look-up table which utilizes solar inlet temperature to the Rankine and condenser water temperature. The look-up table was prepared under laboratory conditions. However, the actual Rankine engine efficiency was lower than that from the look-up table. Therefore, the electrical energy savings may be overestimated.

Alternate Method

An alternate method for computing gross cooling electrical energy savings is by comparing the coefficient of performance of the air-conditioner in the auxiliary mode with that of the total system in Rankine assist mode. These are calculated using the values from Table 2-6 as follows:

Cooling Load = 239.4×10^6 Btu

Auxiliary Energy = 50.9×10^6 Btu(e)

"COP" $= \dfrac{239.4 \times 10^6}{50.9 \times 10^6} = 4.71$

Total System (with Solar)

Cooling Load = 346.9×10^6 Btu

Auxiliary Energy = 65.3×10^6 Btu

"COP" = $\dfrac{346.9 \times 10^6}{65.3 \times 10^6} = 5.31$

Gross Cooling Electrical Energy Savings = $\dfrac{1}{4.71} - \dfrac{1}{5.21} \times 346.9 \times 10^6$

= 8.35×10^6, Btu(e) [= 2448 kWh(e)]

Solar Specific Operating Energy (Table 3-1) = 9.2×10^6, Btu(e) [= 2696 kWh(e)]

Net Electrical Energy Savings for OTP = $(8.35 - 9.20)\ 10^6 = -0.85 \times 10^6$, Btu(e) [-248 kWh(e)]

The fossil savings are the same as before i.e., 19.7 MMBtu. The monetary savings for the OTP is $82.

SECTION 5
MAINTENANCE

Occasionally, unexpected maintenance to the system was necessary to maintain system performance at an acceptable level. This maintenance is listed below;

- debris (pine needles, insects, pollen, etc.) entering the sump tank,
- control thermostats developed an offset,
- faulty temperature/pressure relief valve,
- faulty seal in primary loop pump, and
- condensate developed between the collector glazing.

Debris entered the sump tank through the cooling tower and accumulate in the Rankine-cycle turbine and water chiller condenser lines. This accumulation of debris reduced the flow through the condensers and adversely affected the performance of the R/C-A/C. It was periodically necessary to blow-down the condenser lines and clean the strainers when flow was restricted.

The control thermostats used to determine when the system should cool from storage and when the cooling tower fan should be activated developed offsets. As a result the setpoints for these thermostats had to be changed to maintain proper system performance.

The faulty temperature/pressure relief valve in the domestic hot water system would vent lukewarm water whenever there was hot water usage during a period from 4/8/81 to 6/28/81.

This premature venting of water gave erroneous temperature readings at the outlet of the auxiliary gas-fired water heater during hot water consumption (see Subsection 2.3.2).

The faulty seal in the primary loop pump (P_1) resulted in a system shut-down from 7/10/81 - 8/6/81. The pump was leaking water/glycol mixture and allowing air into the primary loop piping, reducing the performance of the collector array and giving inconsistent readings from the primary loop flow meters. The primary loop piping was drained, the pump seal was replaced, and the system was refilled with a fresh water/glycol mixture.

A continuing problem during the operational test period was the condensation of water between the two plates of glass in the solar collectors. A method was developed to vent the area between the panes of glass. This method appears to have lessened the condensation problem.

SECTION 6
SUMMARY AND CONCLUSIONS

The system performance evaluation in this report provided a summary of the system over the test period (April 1981 through August 1981) of the solar heating and cooling system located in Ocmulgee, Georgia. The system consisted of 5040 square feet of double glazed flat plate collectors, a 4000 gallon thermal storage tank to provide thermal energy primarily for space heating, a domestic hot water subsystem, a developmental organic Rankine cycle engine to provide part of shaft power needed for space cooling by a vapor compressor and a microprocessor based control system to provide for automatic solar system operation. The analysis was conducted by evaluation of measured system performance (Site data acquisition and data processing done by Vitro Laboratories) 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 Operational Test Period (OTP) was about 9 percent lower than long term average conditions. In August 1981, the insolation was 31 percent lower than long term average. However, the solar system was inactive during most of August, due to a system problem.

2. The solar system provided energy for the building space heating, space cooling, and hot water loads during the OTP; providing 51 percent of space heating, 16 percent of space cooling and 72 percent of hot water loads. The result was a net energy savings, during the OTP, of 19.7 million Btu of fossil fuel and 2550 kWh of electrical energy. The monetary savings for the OTP was $250.

   There was inadequate data during the OTP, to project the annual solar contribution and energy savings due to space heating. The actual hot water demand was low. The load was an artificial load created by an automatic load device installed specifically to evaluate the hot water subsystem performance. Therefore, the fossil energy savings due to DHW are not real. On an annual basis, however, the fossil savings can be significant due to the space heating loads.

Even though the cooling subsystem performed well during most of the OTP, the cooling supplied was lower than the building demand. This was due to several factors such as, excessive infiltration, higher than calculated design loads, and some system installation problems. The latter was rectified during the OTP.

3. The thermal storage efficiency during summer or cooling months was typically lower than during winter or heating months. In the summer storage is used only for cooling. The storage temperature should be above 170F for the storage cooling mode to be activated. Because of this high temperature requirement for storage usage in summer, the storage energy losses are higher and storage energy utilization is comparatively lower than during winter. In winter during the heating season the storage is discharged down to 120F.

4. The option of cooling from storage is uneconomical. The electrical operating energies required for energy collection and storage and for storage energy discharge are larger than the electrical energy savings resulting from reduced auxiliary energy usage by the vapor compressor motor during cooling. However, charging storage in lieu of available excess heat purging consumes less operating energy.

SECTION 7.0

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

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.

- o 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.
- o 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).
- o COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.
- o 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 include 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 which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often 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 here.
- o DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

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.

- o ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.
- o ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.
- o 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).
- o STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.
- o 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.
- o STORAGE ENERGY LOST (STLOSS) is the amount of energy delivered to the storage medium which is lost to the surroundings. It is calculated as the difference between the energy to storage (STEI) and the sum of the energy from storage (STEO) and the change in stored energy (STECH).

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, 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 which 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 (SCOPE) is the energy intentionally rejected by the purge unit as a solar fluid overtemperature protection 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.

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 required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- FOSSIL FUEL SAVINGS (HSVF) is the gas heating energy which is displaced by solar heating less the cost of the operating energy which is not common between the solar heating subsystem and the auxiliary heating subsystem.

- BUILDING TEMPERATURE (TB) is the average conditioned space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which 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 (per unit area) measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the ambient temperature during the period from three hours before solar noon to three hours after solar noon.

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 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 which is supplied from the air conditioners which is attributable to the solar-powered Rankine cycle engine.
- 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.) which is not intended to directly affect the thermal state of the subsystem.
- 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 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 conditioned space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the ambient temperature during the period from three hours before solar noon to three hours after solar noon.

RANKINE CYCLE SUMMARY

The Rankine cycle summary is a combination of performance factors which outline the performance of the Rankine Cycle Air Conditioner during space cooling and power generation.

- SOLAR ENERGY USED (RSE) is the amount of solar energy supplied from the ECSS to the Rankine cycle engine during operation.

- TURBINE OUTPUT (RANKOUT) is the predicted shaft output of the Rankine cycle engine based on the solar water temperature and flow rate and the condenser water temperature.

- RANKINE THERMAL EFFICIENCY (REFF) is the predicted thermal efficiency of the Rankine cycle engine based on the solar water temperature and flow rate and the condenser 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., sump and feed pumps, controls, condenser fan, etc.).

- OPERATING ENERGY (TCEOPE) is the amount of electrical energy required to support the operation of the Rankine Cycle Air Conditioner (e.g., pumps, parasitics, etc.) which is not intended to directly affect the thermal state of the subsystem.

- <u>POWER GENERATED</u> (PWRGEN) is the electrical energy produced by the auxiliary motor when driven by the Rankine Cycle engine as a generator.
- <u>COOLING PRODUCED</u> (OUTVC) is the amount of thermal energy removed from the conditioned space of the building by all central SCS solar-and auxiliary-powered equipment.
- <u>SOLAR WATER TEMPERATURE</u> (TRANKS) is the mass flow averaged inlet temperature of the solar water during Rankine cycle engine operation.
- <u>CONDENSING WATER TEMPERATURE</u> (TRANKC) is the mass flow averaged temperature of the condenser sump water during Rankine cycle engine operation.

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

The Ocmulgee Site Data Acquisition Subsystem (SDAS) consists of 52 sensors, an electrical junction box and an SDAS module. The descriptions and designations of all sensors are listed in Table B-1 and their locations are shown in Figure B-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 B-1. SDAS Sensor Description (OTS 44)

Designation	Name	Designation	Name	Designation	Name
D001	Pyranometer	T500	Rankin chiller inlet temp	EP501	Rankin net power
D101	Purge flow	T550	Rankin chiller outlet temp	EP502	Rankin engine condenser pump P6 power
D100	Collector flow	T552	Rankin engine condenser outlet temp	EP503	Rankin chiller condenser pump P7 power
D400	Heating flow	T553	Rankin chiller condenser outlet temp	EP504	Cooling tower fan power
T001	Outdoor db ambient temp	T510	Cooling tower sump temp	EP402	Radiation pump power
T100	Collector inlet temp	W100	Collector loop flow rate	EP505	Rankin unit output power
T150	Collector outlet temp	W200	Storage loop storage HX flow rate	EP507	Parasitic power draw by R/C
T101	Purge inlet temp	W400	Bldg heating water flow rate		
T102	Collector loop HX inlet temp	W402	Heating aux HX flow rate		
T152	Collector loop HX outlet temp	W500	Bldg cooling water flow rate		
T200	Storage loop HX inlet temp	W501	Rankin engine solar flow rate		
T250	Storage loop HX outlet temp	W502	Rankin engine condenser flow rate		
T201	Storage tank temp, top	W503	Rankin chiller condenser flow rate		
T202	Storage tank temp, middle	W300	DHW totalizing meter		
T203	Storage tank temp, bottom	F300	DHW aux gas meter		
T400	Heating loop solar HX inlet temp	EP100	Collector loop pump P1 power		
T450	Heating loop solar HX outlet temp	EP101	Purge fan power		
T451	Heating loop aux HX solar outlet temp	EP200	Storage loop pump P2 power		
T402	Heating loop aux HX boiler HWS inlet temp	EP201	Storage tank circulator pump P8 power		
T452	Htg loop aux HX boiler HWR outlet temp	EP400	Bldg heating loop pump P4 power		
T300	DHW preheat tank cold water supply temp	EP401	Boiler heating loop pump P5 power		
T350	DHW heater inlet temp	EP500	Bldg cooling loop pump P3 power		
T351	DHW tank outlet temp				

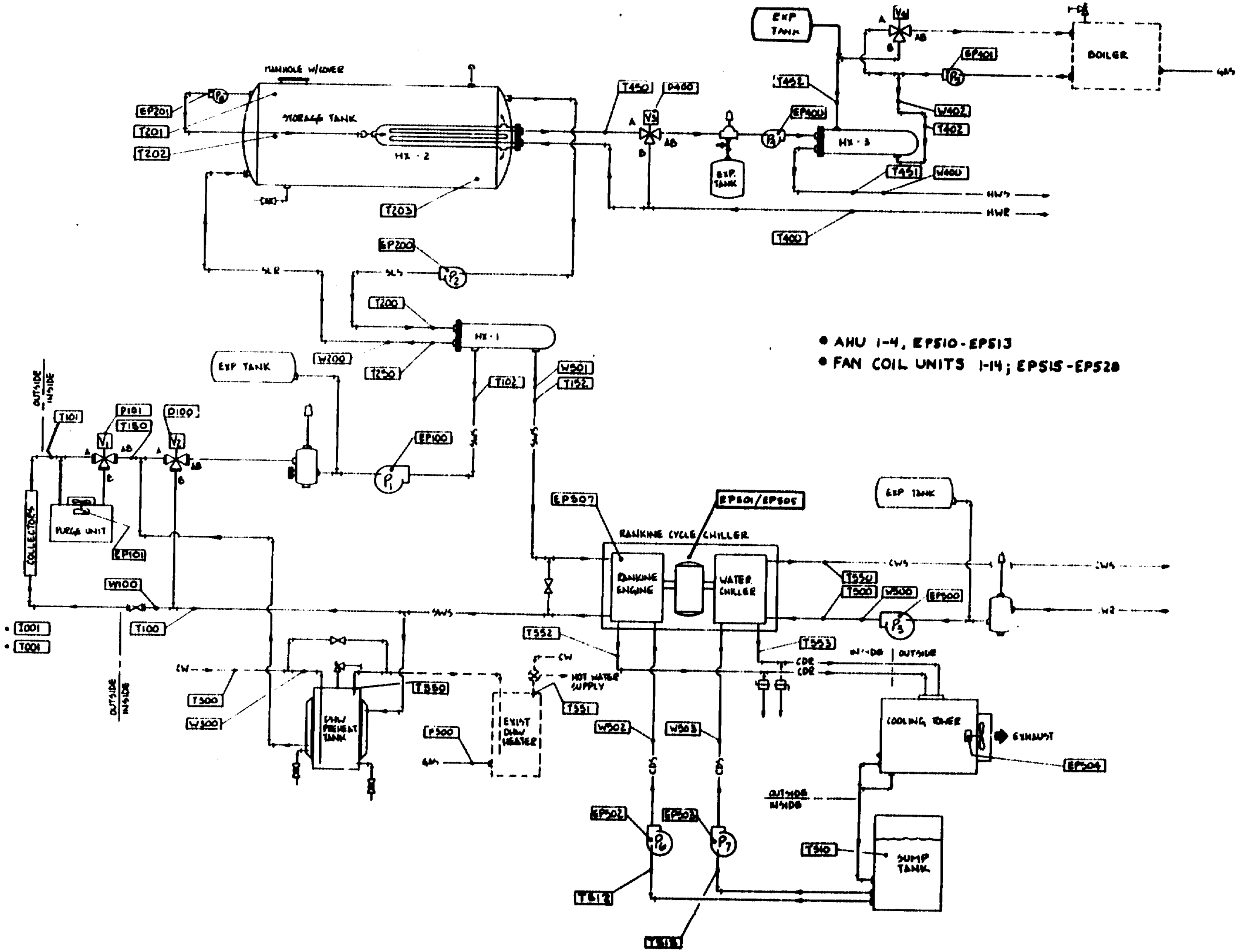

FIGURE B-1. OCMULGEE SITE DATA ACQUISITION SUBSYSTEM SCHEMATIC

APPENDIX C

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 Ocmulgee site, 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 are presented in Table C-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 λt drop across the chiller as opposed to using differential thermocouples on bridge-connected resistance bulbs.

Table C-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	± 0.5°F
FLOW RATE	± 3 PERCENT
POWER (EP SENSORS)	± 2 PERCENT
RANKINE EFFICIENCY	± 5 PERCENT

APPENDIX D
LONG-TERM AVERAGE WEATHER CONDITIONS

The environmental estimates given in this appendix provide a point of reference for evaluation of weather conditions as reported in the Monthly Performance Assessments and Solar Energy System Performance Evaluations issued by the National Solar Data Program. As such, the information presented can be useful in prediction of long-term system performance.

Environmental estimates given in table D-1 for this site include the following monthly averages: insolation on a horizontal plane at the site, insolation in the tilt plane of the collection surface, ambient temperature, heating degree-days, and cooling degree-days. Estimation procedures and data sources are detailed in the following paragraphs.

The preferred source of long-term temperature and insolation data is "Input Data for Solar Systems" (IDSS) [1] since this has been recognized as the solar standard. The IDSS data are used whenever possible in these environmental estimates for both insolation and temperature related sources; however, a secondary source used for insolation data is the Climatic Atlas of the United States [4], and for temperature related data, the secondary source is "Local Climatological Data" [5].

Since the available long-term insolation data are only given for a horizontal surface, solar collection subsystem orientation information is used in an algorithm [6] to calculate the insolation expected in the tilt plant of the collector. This calculation is made using a ground reflectance of 0.2.

Table D-1. Long-Term Average Environmental Estimates

MONTH	NORMAL MONTHLY TEMPERATURE (DEG F)*	NORMAL DEGREE DAYS* BASE 65 DEG F		MEAN DAILY SOLAR RADIATION# (BTU/ft^2)		
		HEATING	COOLING	HORIZONTAL PLANE ($\bar{H}$)	COLLECTOR ARRAYS PLANE ($\bar{H}_T$)	$\bar{H}_T/\bar{H}$
January	47.8	543	10	768.9	969.3	1.26
February	50.4	423	14	1019.7	1208.6	1.19
March	56.5	298	35	1363.3	1504.4	1.10
April	65.8	66	90	1736.2	1776.0	1.02
May	73.5	6	269	1885.1	1817.8	0.96
June	79.6	0	438	1919.4	1804.9	0.94
July	81.4	0	508	1785.3	1700.0	0.95
August	80.9	0	493	1717.8	1710.4	1.00
September	75.8	0	324	1438.8	1535.5	1.07
October	65.7	82	103	1247.1	1470.2	1.18
November	55.2	304	10	939.6	1199.4	1.28
December	48.3	518	0	729.0	944.8	1.30
ANN	65.1	2240	2294	1372.2	1471.1	1.07

* Based on 1941-1970 Period

\# As noted in Solmet Volume 1

MACON, GEORGIA

(Latitude: 3242 N, Longitude: 8339 W)